

GEOLOGY AND GEOCHEMISTRY OF AKAKI VOLCANICS, CYPRUS

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ABSTRACT

The Akaki River section is located on the northern flank of the Troodos ophiolite and comprises a complete cross section through the extrusive series from the underlying sheeted dike complex to the overlying pelagic sediments.

Field data from the Akaki River section set constraints about volcanic processes operating at the sea floor, for the Troodos ophiolite, and may have implications for recent submarine volcanics. The subdivision of the Akaki River section into 12 stratigraphic units was based on the occurrence and characteristics of extrusive lithologic types. One or several of these stratigraphic units represent a cross section through a volcano. A cyclic constructional model for the evolution of the Troodos submarine volcanos was developed. These volcanos have an elongated shape, they are about 100 - 300 m high, up to 800 m wide, and probably up to 1600 m long.

The typical succession of sheet flows, large lava bodies, large lava tubes, and pillow lavas are described both from the Troodos ophiolite and from oceanic ridges. Volcanic construction is episodic in both cases. It is suggested that the mode of construction proposed for the volcanic edifices of the Troodos ophiolite may also be applicable for volcanoes at oceanic ridges today.

A representative suite of whole rocks and fresh volcanic glass samples were collected. Glass samples were carefully handpicked to obtain clean glass separates free of alteration. These glass compositions are interpreted to be fresh for major and trace elements contents and Sr, Nd, Pb, and O compositions. The glasses range in compositions from basaltic andesite to dacite. Incompatible element concentrations in the mafic compositions are low (6-11 x chondritic) and the LREE are strongly depleted. However, the ratios of low field strength elements (K, Rb, Cs, Sr, Ba) to high field strength elements (Ta, Ti, Hf) and REE are higher than those in N-MORB. Nd isotopic compositions show a very small range with ϵ_{Nd} of +6.5 to +7.5. Initial $^{87}Sr/^{86}Sr$ range from 0.7032 to 0.7040. Pb isotopes have a restricted range with $^{206}Pb/^{204}Pb$ (18.59 - 18.70), $^{207}Pb/^{204}Pb$ (15.55 - 15.90), $^{208}Pb/^{204}Pb$ (38.08 - 38.50). The oxygen isotope compositions for fresh glasses fall in the range reported for fresh mafic mantle derived

volcanics, with $\delta^{18}\text{O}$ varying from 5.4 to 6.5.

Earlier subdivisions of the extrusive series into Upper and Lower Pillow lavas, and into an andesite - rhyolite and overlying more mafic series were only partly verified. The stratigraphic - compositional trend is essentially continuous for most chemical elements. A well defined step is present primarily for TiO_2 . However, even this component cannot be used as a strict stratigraphic discriminant.

The major and trace element characteristics of the Troodos glasses, including their volatile content, are similar to those found in supra-subduction zone volcanics. For the first time in the study of the Troodos volcanics, it has been possible to extend the comparison with modern volcanics for LFS elements. As a result, an origin at a major ocean basin spreading ridge is precluded. Comparison of the geological and geochemical evidence from Troodos and that from supra-subduction zone environments today suggest that the Troodos ophiolite formed in the earliest stages of island arc development rather than in a back arc basin environment.

The freshness of the glasses permitted to constrain the processes operating in the generation of the Troodos magmas. The observed range of chemical compositions of the glasses suggests that the Troodos magma source is heterogeneous. Major element compositions are consistent with fractional crystallization of an ol-cpx-plag or opx-cpx-plag assemblage. The trace element characteristics, however, can be explained only in part by fractional crystallization and different degrees of partial melting. The trace element and isotopic compositions, e.g. the high Pb and low Nd isotopic ratios of the Troodos volcanics can be convincingly explained by mixing of mantle components from a subduction zone environment, namely a variably depleted mantle end member and subducted sediment. Differences in LFS element ratios such as Ba/Rb are observed in the glasses and cannot be accounted for with a simple two component mixing model. They indicate the presence of a third component in the mantle source. This is presumably a water-soluble element-rich fluid phase derived from dehydration of the subducted slab.

ZUSAMMENFASSUNG

Der Akaki Canyon befindet sich an der Nordflanke des Troodos Ophioliths. Dieses Profil erstreckt sich über die gesamte extrusive Serie, vom darunterliegenden Gangschwarm bis zu den überlagernden pelagischen Sedimenten.

Geländebeobachtungen im Akaki Canyon lassen Rückschlüsse auf die Extrusionsprozesse am Meeresboden des Troodos Ophioliths zu, und diese lassen sich unter Umständen auch auf rezente submarine Vulkanite anwenden. Der Akaki Canyon wurde mit lithologischen Kriterien in 12 stratigraphische Einheiten unterteilt, die überwiegend aus Pillowlaven oder Lavaströmen bestehen. Eine oder mehrere dieser Einheiten stellen einen Querschnitt durch einen Vulkan dar. Ein Modell für die Entstehung solcher Vulkane wurde entwickelt. Diese Vulkane haben eine längliche Form, sind etwa 100-300 m hoch, bis zu 800m breit und wahrscheinlich bis zu 1600 m lang.

Die für den Akaki Canyon typische Abfolge von Lavaströmen, unregelmäßigen Lavamassen, großen Lavaröhren und Pillowlaven sind auch von rezenten Ozeanrücken beschrieben worden. Der Aufbau der Vulkane erfolgt in beiden Fällen episodisch. Dieses läßt vermuten, daß das Entstehungsmodell für die Vulkane in Troodos auch für rezente submarine Vulkane gelten könnte.

Frische vulkanische Gläser und Gesamtgesteinsproben wurden im Akaki Canyon gesammelt. Die Glasproben wurden sorgfältig von Hand ausgelesen, um alterationsfreie Glasseparate zu erhalten. Diese Gläser wurden analysiert und können in ihrer chemischen Zusammensetzung als frisch angesehen werden. Konzentrationen von inkompatiblen Spurenelementen sind in den mafischen Gläsern niedrig (6-11 x chondritisch), außerdem sind die LREE sehr verarmt. Dagegen sind die Verhältnisse von low field strength elements (K, Rb, Cs, Sr, Ba) zu high field strength elements (Ta, Ti, Hf) und REE höher als die in N-MORB. Die Isotopenzusammensetzung von Nd schwankt nur gering mit ϵ_{Nd} von +6.5 bis +7.5. Initiale $^{87}Sr/^{86}Sr$ Verhältnisse bewegen sich zwischen 0.7032 to 0.7040. Die Pb Isotopenzusammensetzung zeigt nur eine geringe Variation mit $^{206}Pb/^{204}Pb$ (18.59 - 18.70), $^{207}Pb/^{204}Pb$ (15.55 - 15.90) und $^{208}Pb/^{204}Pb$ (38.08 - 38.50). Die Sauerstoffisotopenzusammensetzung der Troodos Gläser ist der von frischen

Mantelgesteinen mit $\delta^{18}\text{O}$ zwischen 5.4 und 6.5 sehr ähnlich.

Frühere Unterteilungen der Extrusiven Serie in Upper und Lower Pillow Lavas und in eine Andesit-Rhyolith Serie und eine darüberliegende mafische Serie konnten nur zum Teil bestätigt werden. Der stratigraphisch-chemische Trend ist für die meisten Elemente kontinuierlich. Eine deutliche Abstufung ist nur für TiO_2 möglich.

Die Konzentrationen von Haupt- und Spurenelementen in Troodos Gläsern, unter anderem ihr Gasgehalt, sind denen von Supra-Subduktionszonenvulkaniten sehr ähnlich. Zum ersten Mal bei Untersuchungen des Troodos Ophioliths konnten auch alterationsempfindliche Spurenelemente und Isotope zum Vergleich mit rezenten submarinen Vulkaniten herangezogen werden. So konnte die Entstehung der Troodoslaven an einem Mittelozeanischen Rücken ausgeschlossen werden. Ein Vergleich mit Vulkaniten von rezenten Randbecken und Inselbögen zeigt daß Troodos wahrscheinlich eher in einem frühen Inselbogenstadium, als in einem Randbecken entstanden ist.

Die Frische der vulkanischen Gläser läßt Rückschlüsse auf die Prozesse der Magmenentstehung zu. Die chemische Zusammensetzung der Gläser deutet auf eine heterogene Mantelzusammensetzung hin. Hauptelementkonzentrationen stimmen mit fraktionierter Kristallisation von ol-cpx-plag oder opx-cpx-plag überein, dagegen lassen sich die Spurenelementkonzentrationen und -verhältnisse mit fraktionierter Kristallisation und/oder verschiedenen Graden der partiellen Aufschmelzung allein nicht erklären. Die hohen Pb- und niedrigen Nd-Isotopenzusammensetzungen lassen sich durch eine Mischung von verschiedengradig verarmtem Mantel und subduziertem Sediment deuten. Die Variation in manchen Spurenelementverhältnissen sind jedoch auch nicht auf diese Zweikomponentenmischung zurückzuführen. Das deutet auf eine dritte Komponente im Mantelbereich der Troodosmagmen hin. Diese Komponente ist reich an wasserlöslichen Spurenelementen und ist wahrscheinlich eine fluide Phase, die durch Entwässerung der subduzierten Platte entstand.

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CHAPTER 1. INTRODUCTION

The term "ophiolite" was originally used by Brongniart (1827) to describe serpentinite. Steinmann (1906, 1927) defined ophiolite as an association of peridotite (serpentinite), gabbro, diabase, spilite and deep water sediment, extending the term to describe an association of rocks rather than one single rock type. This definition was based on the theory that ophiolites formed as thick magmatic extrusions, emplaced in the early stages of eugeosyncline development (see Coleman, 1977, for a summary).

More recently, the theory of plate tectonics provided a new framework for the interpretation of origin and emplacement of ophiolites. Seismic refraction studies have shown that the oceanic crust is layered, layer 1 consists of sediments, layer 2 of basalts, layer 3 of sheeted dikes and gabbros, and layer 4 is thought to represent upper mantle. A comparison with ophiolites shows very similar successions (e.g. Christensen & Salisbury, 1975, Coleman, 1977). Further, the sheeted dike complex observed in ophiolites was interpreted as indication for spreading processes (Moores & Vine, 1971, Kidd & Cann, 1974). Drilling into the ocean floor recovered sediments, basalts, and sheeted dikes and confirmed the similarity between oceanic crust and ophiolite successions. Several authors proposed that ophiolites were fragments of oceanic crust obducted onto continental margins (Coleman, 1971, Dewey & Bird, 1971, Davies 1971, Moores & Vine, 1971, Church, 1972, Coleman, 1977), and this interpretation is supported by the fact that the lithology of oceanic crust is similar to that of ophiolites.

The 1972-Penrose Conference on ophiolites (Anonymous, 1972) redefined the term ophiolite as an assemblage of mafic and ultramafic rocks with specific compositions and stratigraphic sequence (Table 1). From base to top, an ophiolite complex consist of (1) an ultramafic complex, harzburgite, often tectonized; (2) a gabbroic complex with cumulus textures; (3) mafic sheeted dikes; (4) mafic volcanics, often pillowed, and (5) overlying pelagic sediment. Faults may be common, and parts of this succession may be missing. The term ophiolite is independent of the origin of these rocks, but ophiolites were widely believed to represent fragments of oceanic crust formed at constructive

plate margins.

Table 1. The complete ophiolite sequence as defined at the Penrose Ophiolite conference in 1972.

```

basic volcanics
(commonly pillowed)
-----
merging into-----
basic sheeted dike complex
-----
trondhjemites      }
                    } high level intrusives
gabbros             }
                    }
                    }
olivine gabbros     }
pyroxenites         } layered cumulates
peridotites         }
                    }
-----
harzburgite* (sometimes lherzolite, dunite,
and chromitite with a metamorphic tectonized fabric)
* commonly serpentized

```

Recent oceanic crust has been studied in situ by direct observation from submersibles, or drilling to shallow depths of a few hundred meters. In ophiolites, however, studies of the vertical structure and internal relationships are possible. As a result, petrologists and geophysicists have drawn on ophiolites to constrain the nature of oceanic crust formed at major oceanic spreading ridges.

More recently, it has been recognized that many ophiolites have physical, petrological and geochemical characteristics different from those observed at modern, major ocean basin spreading ridges. Examples of such differences are: (a) the smaller thickness of the crustal section in ophiolites (Davies, 1971); (b) the common occurrence of more highly differentiated rock types such as andesites and dacites (Miyashiro, 1973); and (c) differences in trace element and isotopic compositions between ophiolites and oceanic crust (e.g. Pearce & Cann,

1973, Peterman et al., 1971). If conclusions about the nature of oceanic crust are to be drawn from ophiolites, it is essential to know if these ophiolites formed under conditions comparable to normal oceanic crust today with respect to structure, chemical composition, and tectonic setting.

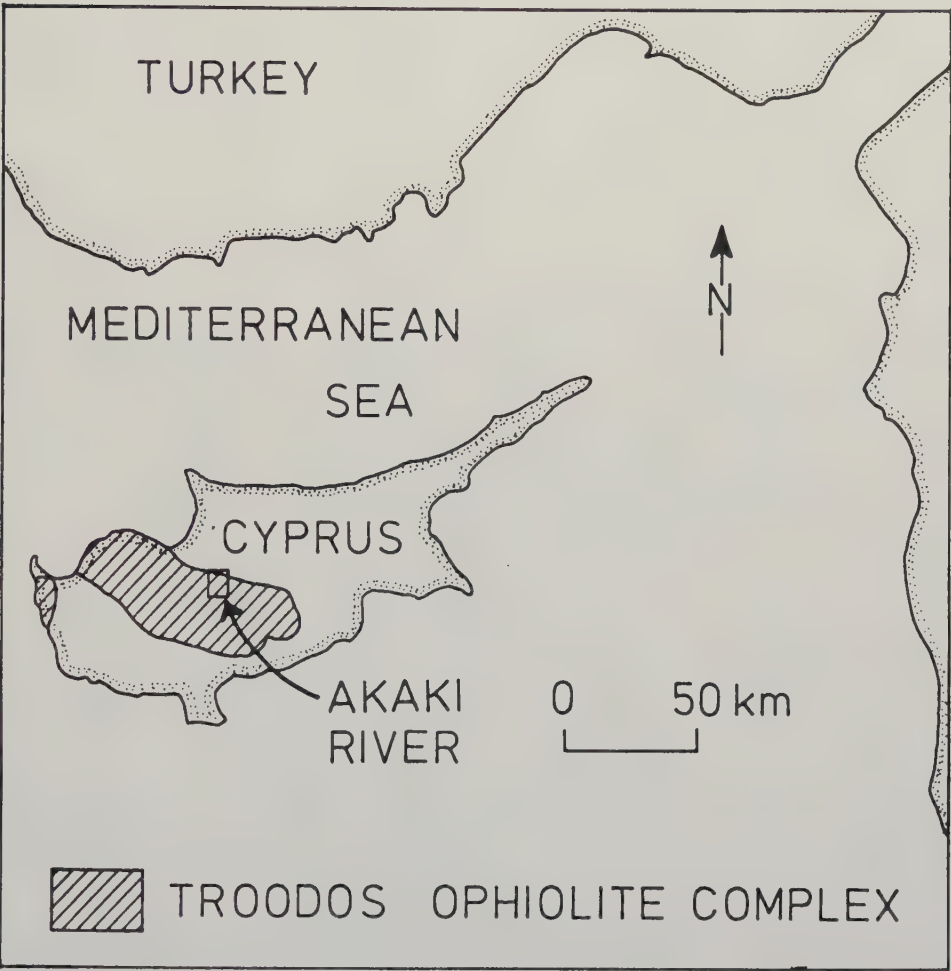


Fig. 1.1 The island of Cyprus in the eastern Mediterranean Sea.

In this study the extrusive series of the Troodos ophiolite along the Akaki River Canyon on the island of Cyprus in the eastern Mediterranean was investigated in detail (Fig. 1.1). It was undertaken as a part of the Cyprus Study Project of the International Crustal Research Drilling Group comprising mapping and drilling in all members of the Troodos ophiolite.

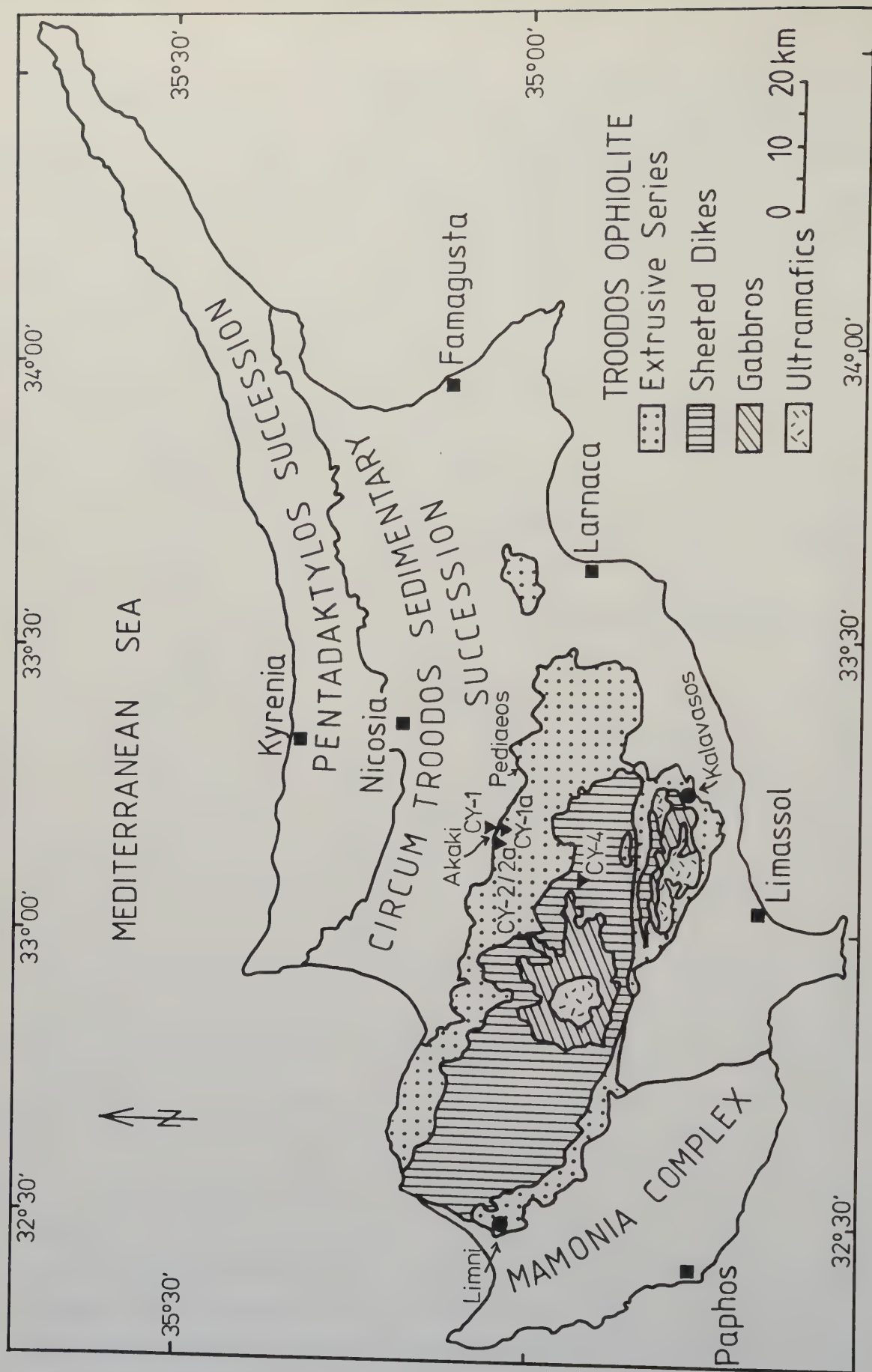


Fig. 1.2. Simplified map of the Troodos ophiolite (after Bednarz & Schmincke, submitted).

The Troodos ophiolite represents one of the earliest recognized and best documented examples of an ophiolitic association. It contains all elements required by the Penrose definition: tectonized harzburgite, mafic cumulates, a sheeted dike complex, submarine volcanics, and pelagic sediments (Fig. 1.2, 1.3). The rock types occur in an annular structure, dipping outwards. The lowest member of the sequence, the harzburgite, is located in the center of the complex, surrounded and overlain by cumulates, a sheeted dike complex, and an outer ring of submarine volcanics (Fig. 1.2, 1.3). Gass (1968), Moores & Vine (1971), and Gass & Smewing (1973) interpreted this association

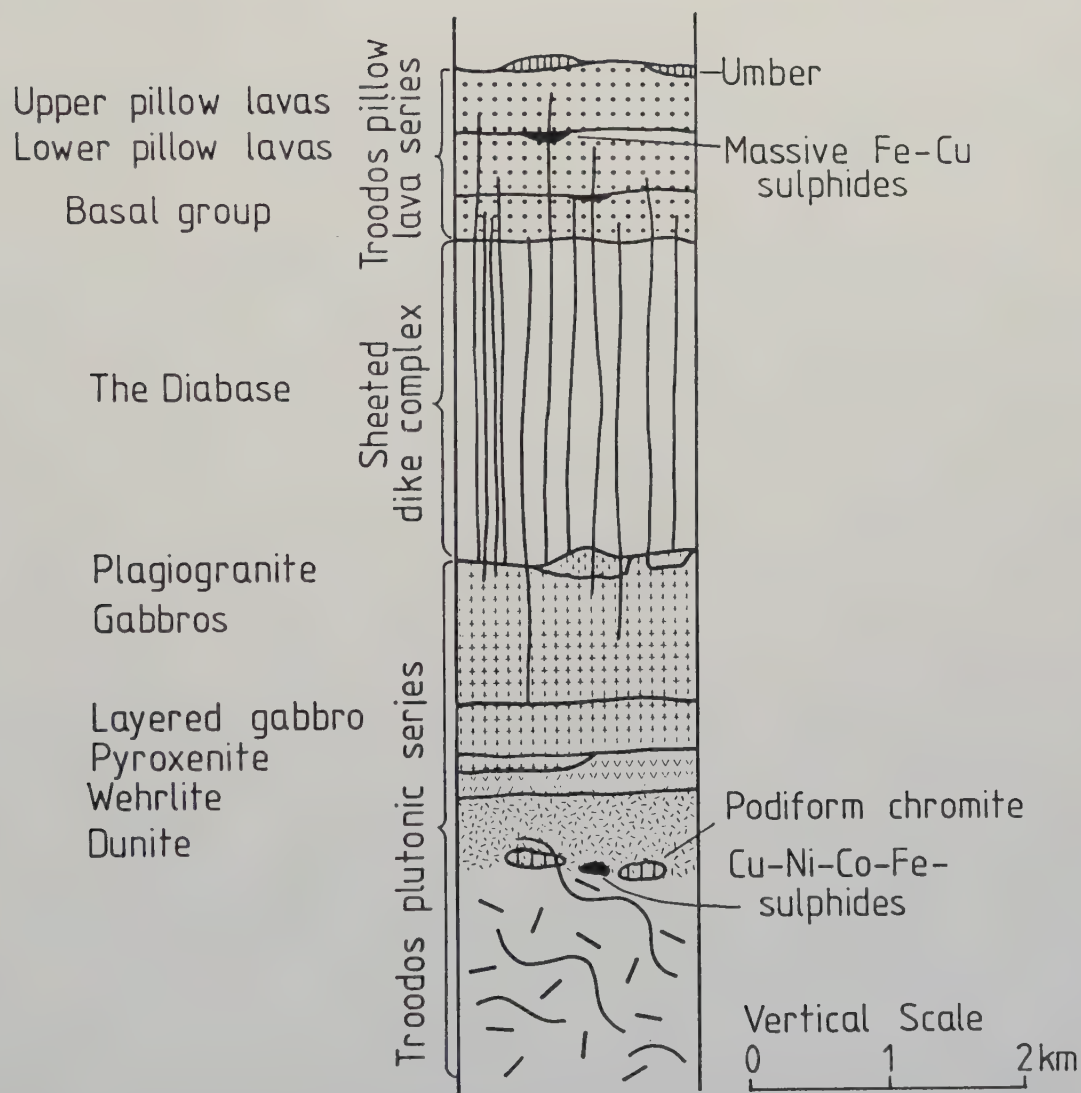


Fig. 1.3. Lithostratigraphic section of the Troodos ophiolite (after Searle & Panayiotou, 1980).

of rocks as an ophiolite, and as a fragment of oceanic crust generated at a major oceanic spreading axis.

On the basis of geochemical data, other workers have proposed that the Troodos ophiolite formed in an island arc (Miyashiro, 1973) or, less specifically, in an environment influenced by a subduction zone (supra-subduction zone) (Pearce, 1975, 1980, McCulloch & Cameron, 1983, Robinson et al., 1983, Schmincke et al., 1983).

Early workers divided the extrusive series into the Upper Pillow Lavas (UPL), and the Lower Pillow Lavas (LPL) on the basis of silica saturation, color, abundances of olivine phenocrysts, secondary minerals, and the location of the sulfide orebodies (Wilson, 1959, Bear, 1960, Gass, 1960). Gass & Smewing (1973) divided the extrusive series into an axis sequence, consisting of the Lower Pillow Lavas and the sheeted dikes, and a younger, off-axis sequence, represented by the Upper Pillow Lavas. They proposed a metamorphic discontinuity within the extrusive series.

Recent studies (Robinson et al, 1983, Schmincke et al. 1983) have subdivided the extrusive series of the northern flank of the ophiolite into two geochemical suites on the basis of volcanic glass compositions: a lower andesite-dacite-rhyolite assemblage of arc tholeiite affinity and an upper picritic basalt suite with depleted arc tholeiite affinity. The stratigraphic level of this boundary is variable within the extrusive series in relation to the old Upper Pillow Lava - Lower Pillow Lava boundary.

The Akaki River section, a complete cross section through the extrusive series at the northern flank of the ophiolite was recently remapped and subdivided in twelve distinct stratigraphic units made up of pillow lavas, sheet flows, hyaloclastite breccias, and dikes and sills (Schmincke et al, 1983). Each of these units is interpreted to represent a section through a volcanic edifice erupted in a relatively short period of time.

The aims of this study are:

(1) to map the extrusive series along the Akaki River section in detail and to characterize the volcanics and their petrography, as well as volcanic edifices and their evolution through time (Chapters 2 and 3);

(2) to analyze a representative suite of fresh volcanic glasses and whole rocks for major and trace elements and isotopic compositions (Chapter 4);

(3) to assess the freshness of the volcanic glasses and whole rocks and to characterize the primary volcanic compositions of the Troodos extrusives (Chapter 5);

(4) to analyze the chemical relationships within the volcanics and evaluate earlier subdivisions of the extrusive series (Chapter 6);

(5) to compare Troodos extrusives with published data on volcanics from constructive and destructive plate margins to constrain the tectonic setting of the Troodos ophiolite (Chapter 7);

(6) to characterize the mantle source(s) and the processes operating in the genesis of Troodos magmas (Chapter 8).

CHAPTER 2. VOLCANOLOGY OF THE SUBMARINE LAVAS OF THE AKAKI CANYON

2.1 INTRODUCTION

In order to study the volcanic constructional processes operating during the formation of the volcanic layer of the Troodos ophiolite, a cross section through the extrusive series of the Troodos ophiolite was mapped in detail. The Akaki River canyon between the villages of Malounda and Klirou was chosen, because a complete section through the extrusive series (i.e. from the sheeted dike complex to the overlying pelagic sediments) is well exposed (Fig 2.1, Fig 2.2). This section was also sampled for geochemical and petrological studies (Fig. 2.2). A brief description of the samples is given in the Appendix (Table A.1).

In this chapter the field evidence from the Akaki River section is presented. This includes a description of the major volcanic and intrusive rock types (section 2.2), the stratigraphy of the extrusive series and the subdivisions into stratigraphic units A to L (section 2.3). The characteristics of the Troodos volcanics are compared to recent submarine volcanics (section 2.4). Finally a model for the structure and evolution of a typical submarine pillow volcano is based on the data from the Akaki River section (section 2.5).

2.2 LITHOLOGIC TYPES

The extrusive series of the Troodos ophiolite contains the following rock types in order of relative abundance: 1. pillow lavas; 2. large bodies and large tubes; 3. sheet flows; 4. dikes and sills; 5. extrusive breccia; and, 6. talus breccia. The chemical composition of the volcanic rocks ranges from basaltic andesite to dacite, independent of the lithologic type, e.g. pillow lavas or sheet flows.

2.2.1 PILLOW LAVAS

Pillow lavas make up the bulk of modern ocean floor volcanics (Moore, 1975). They are round to elongate shaped in cross section, and have quenched, often glassy rims. However, in three dimensions, pillow lavas are tubes (Moore, 1975, Ballard & Moore, 1977). They form when lava is erupted under water. The surface of lava erupted is then immediately quenched by water, forming a sealing skin, while inside the newly formed tube, the lava continues to flow (Moore, 1975, Ballard &

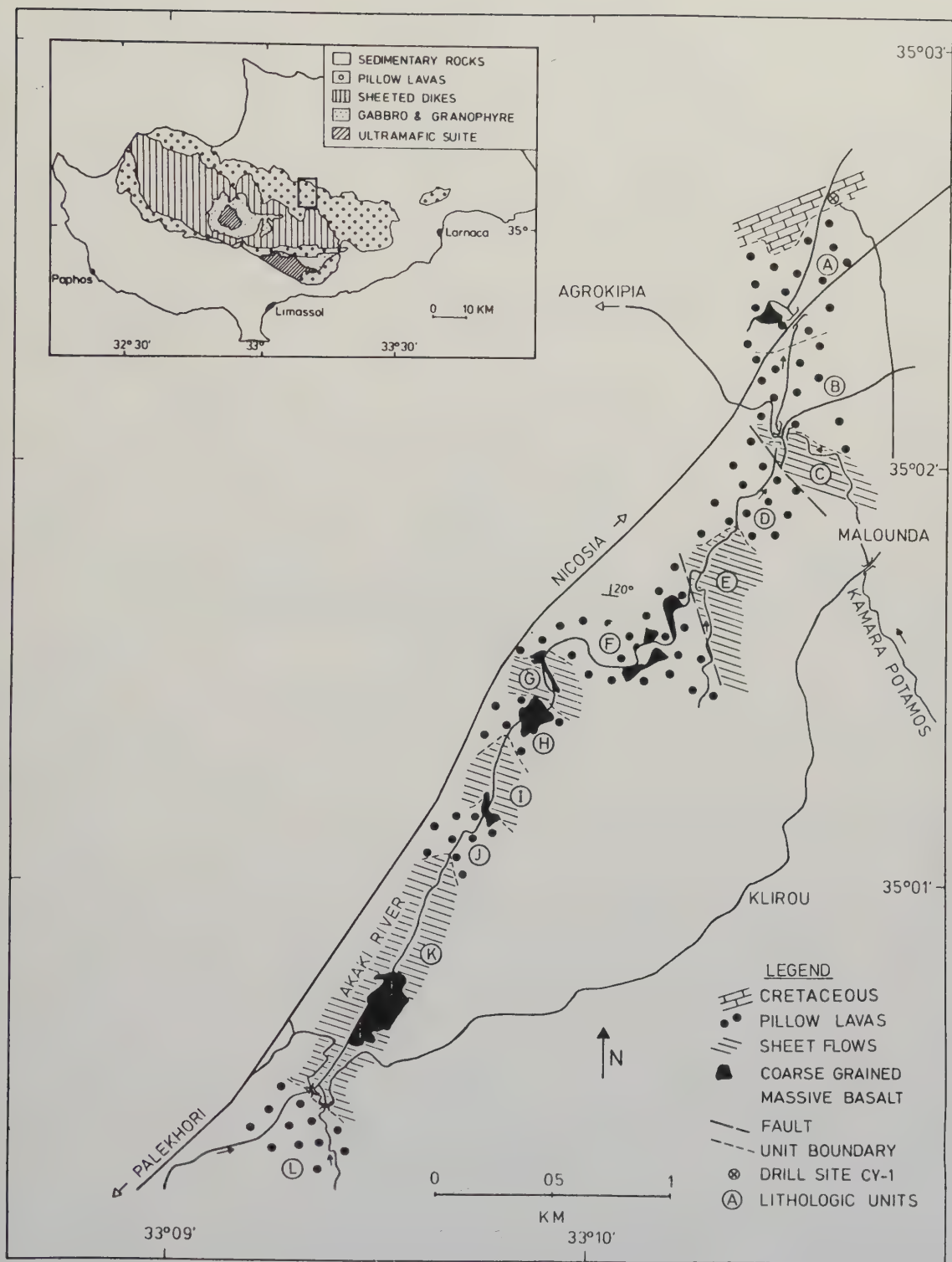


Fig. 2.1. Map of the Akaki River section showing lithology and stratigraphy. Inset shows study area on Cyprus. Schematic stratigraphic section is shown at right.

Moore, 1977). When the lava supply continues, lava tubes expand or break up, forming new "buds" and branches to allow higher flow rates of lava.

Pillow lavas are the most common lithologic type in the Akaki River section (Bear, 1960). A typical pillow is about 1 m in diameter. In cross section (from top to bottom), an often glassy margin (0.5 to 1 cm wide) is followed by a highly vesicular zone of up to 15 cm. In this zone the vesicles may be up to 5 mm in diameter, but range mostly from 3 to 4 mm. Vesicles may be elongated in the flow direction of the pillow. Due to the high vesicle content in this top zone, the rock may be highly weathered. In the top half, larger pillows may show smaller

Fig. 2.2. Detailed geologic map of the Akaki River section. Lithologic types, faults, boundaries of stratigraphic units and sample locations are shown.

Legend for geologic maps

-  pillow lava
-  large tubes
-  extrusive breccia & hyaloclastites
-  sheet flows
-  large irregular bodies
-  dikes & sills
-  talus breccia, volcanic
-  pelagic sediment
-  hydrothermally altered zone
-  unit boundary
-  fault
-  cliff
-  dip
-  unit
-  sample location

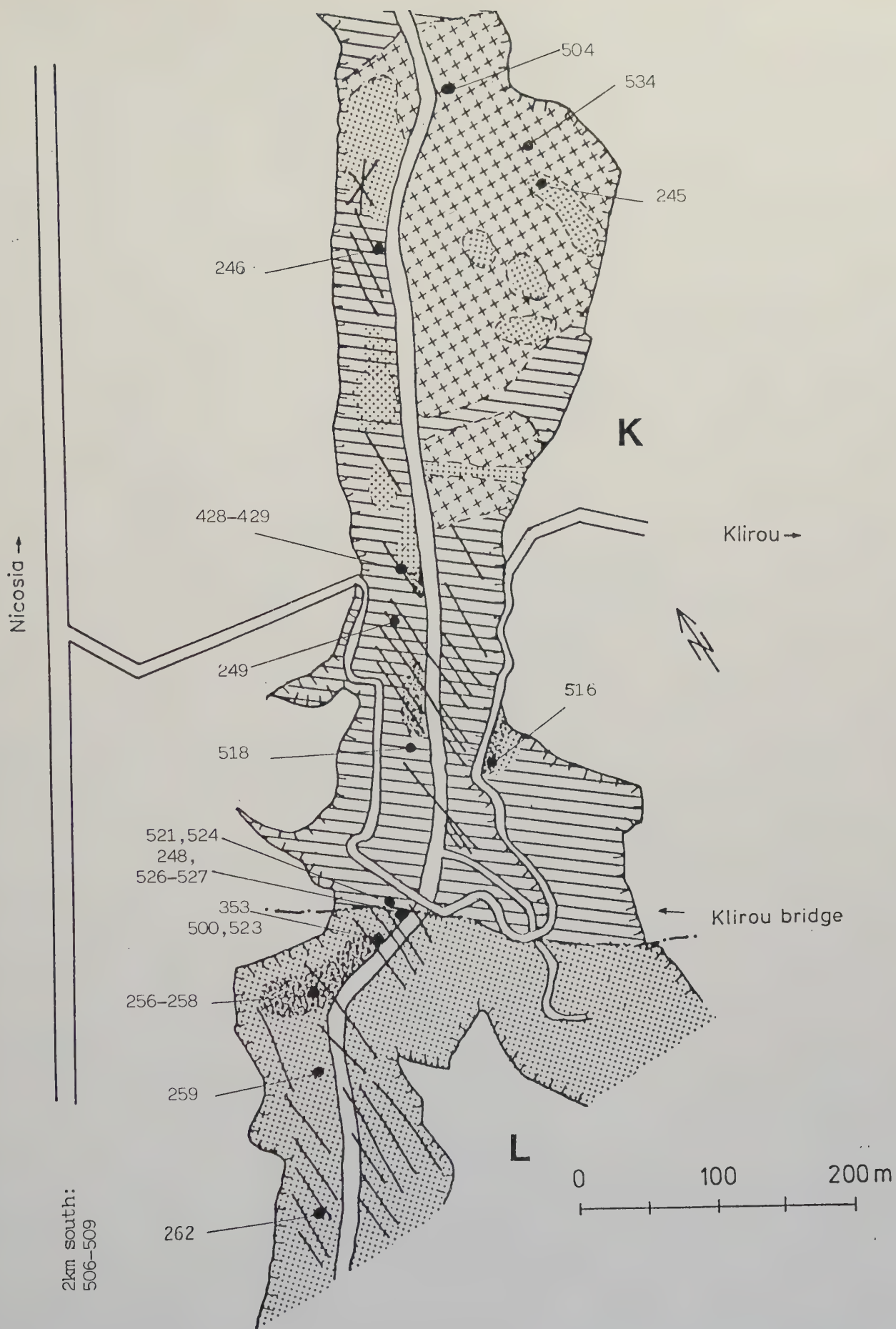


Fig. 2.2a. Detailed geologic map of units K and L.

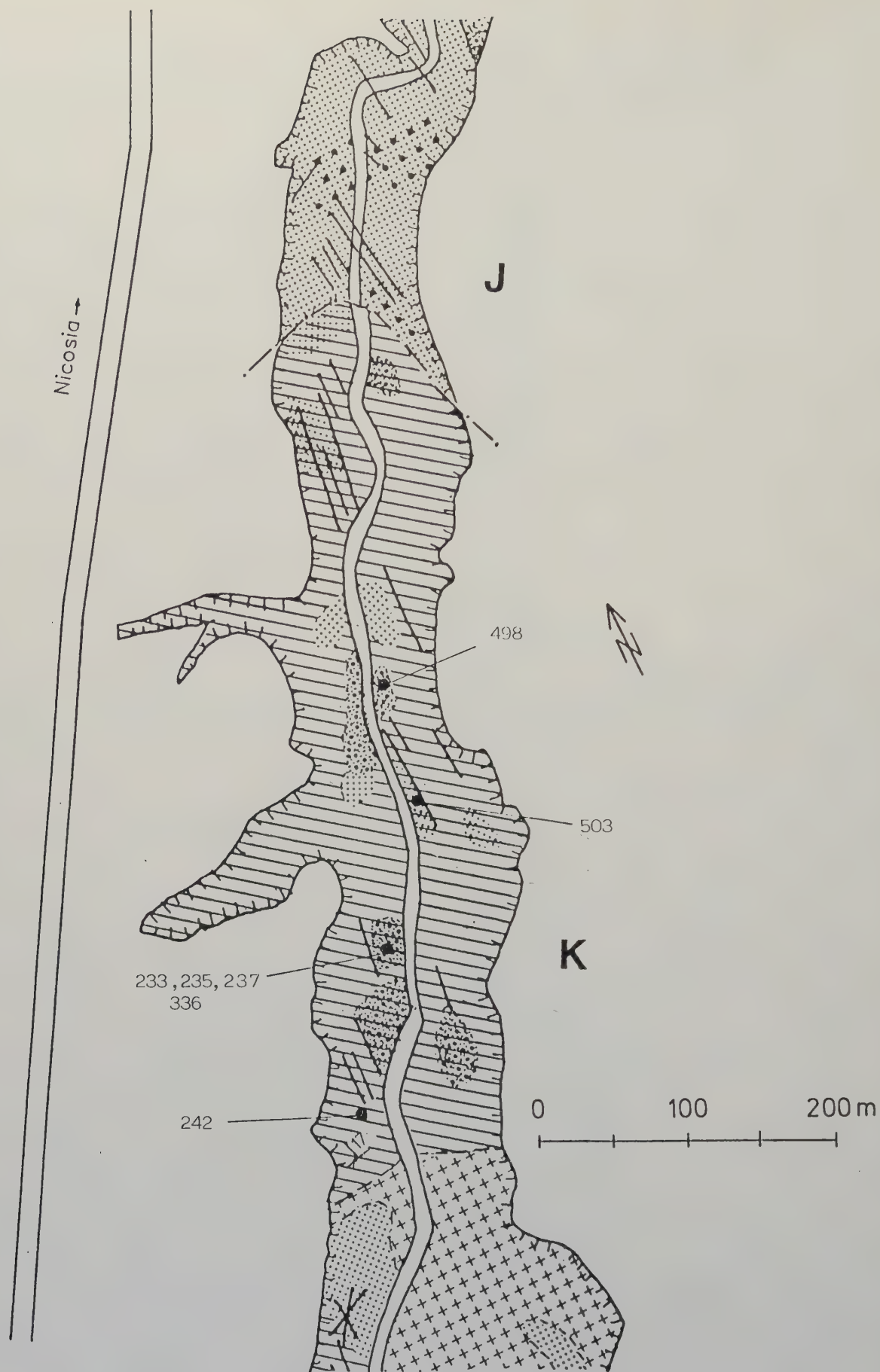


Fig. 2.2b. Detailed geologic map of unit K.

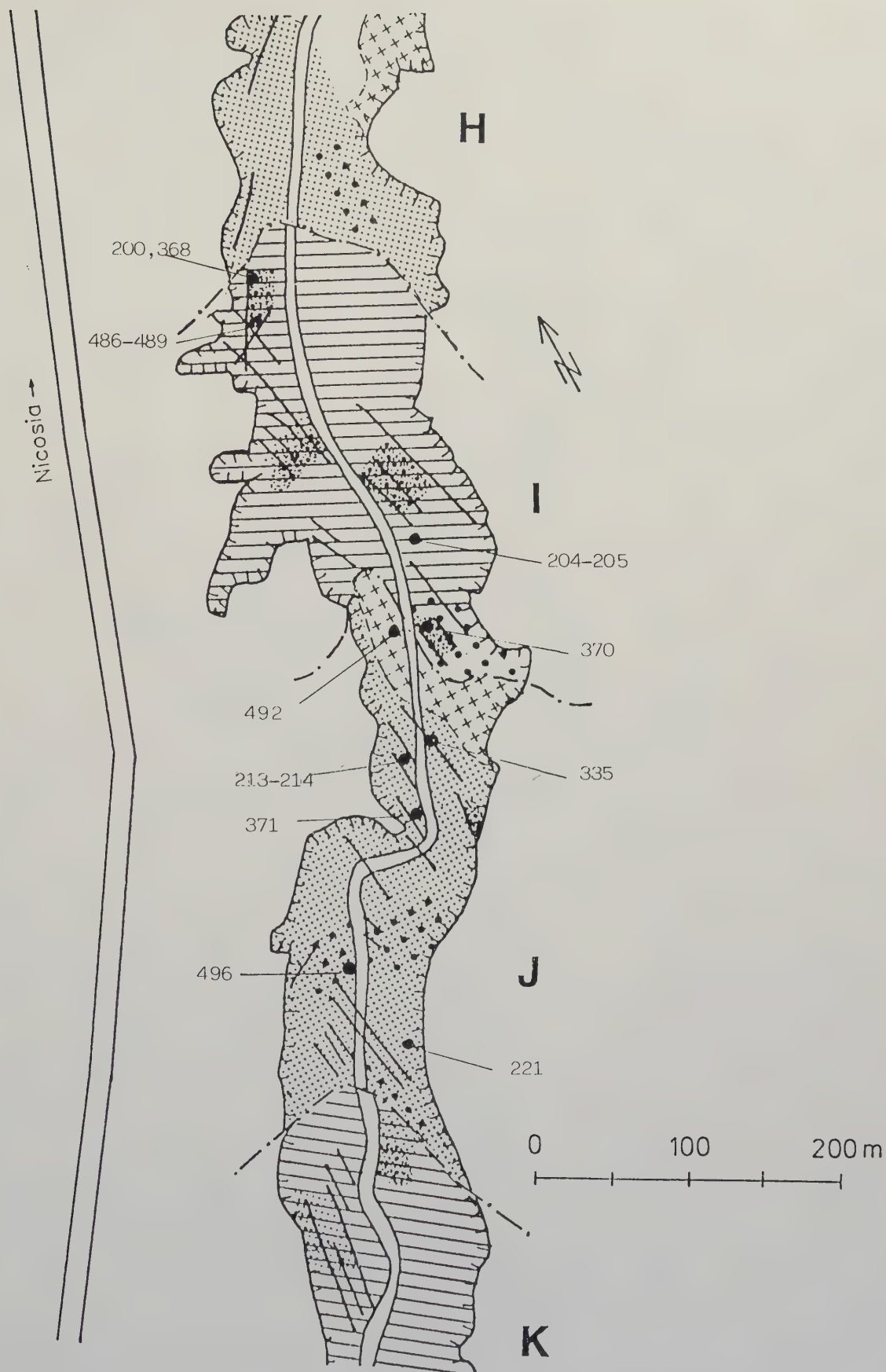


Fig. 2.2c. Detailed geologic map of units I and J.

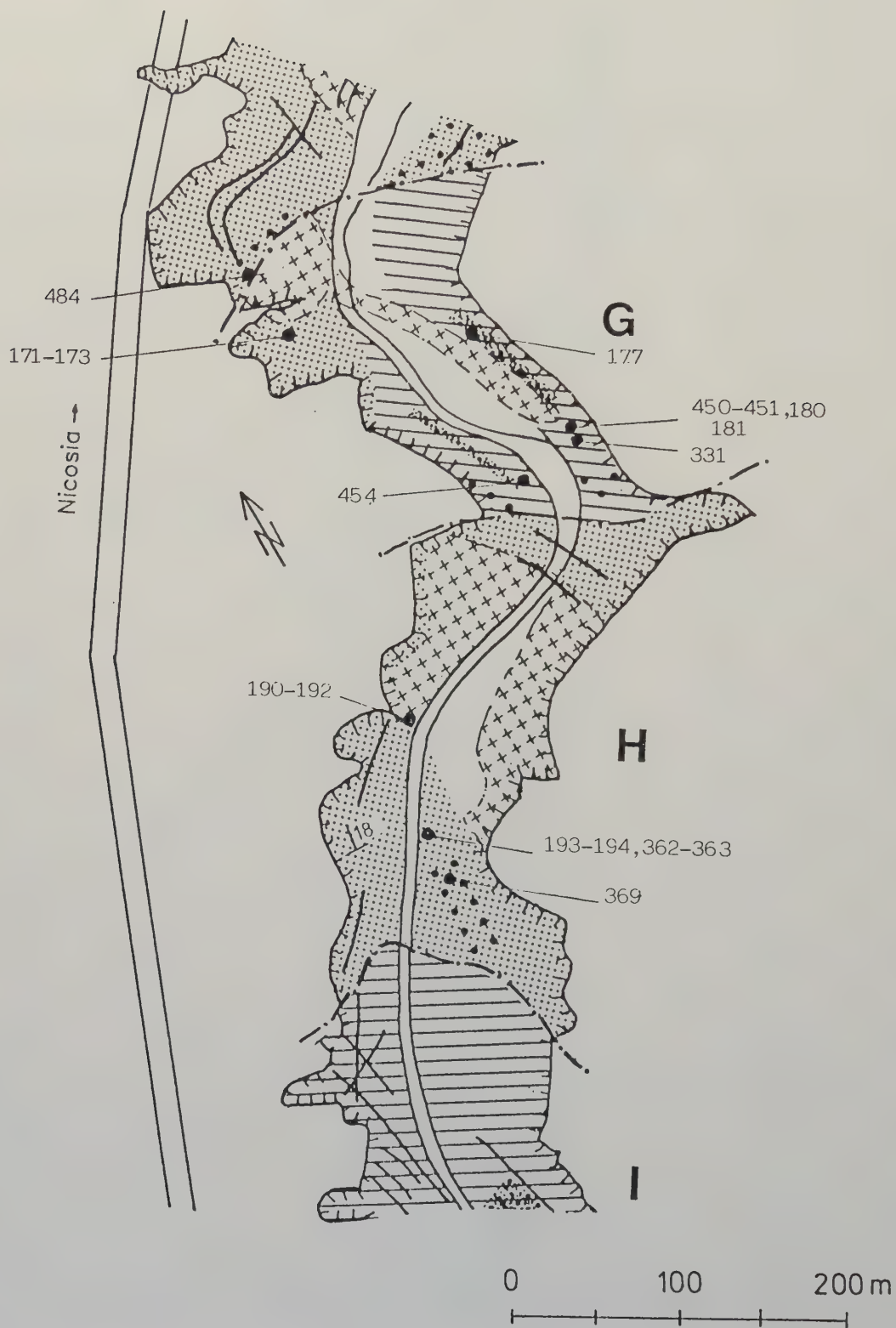


Fig. 2.2d. Detailed geologic map of units G and H.

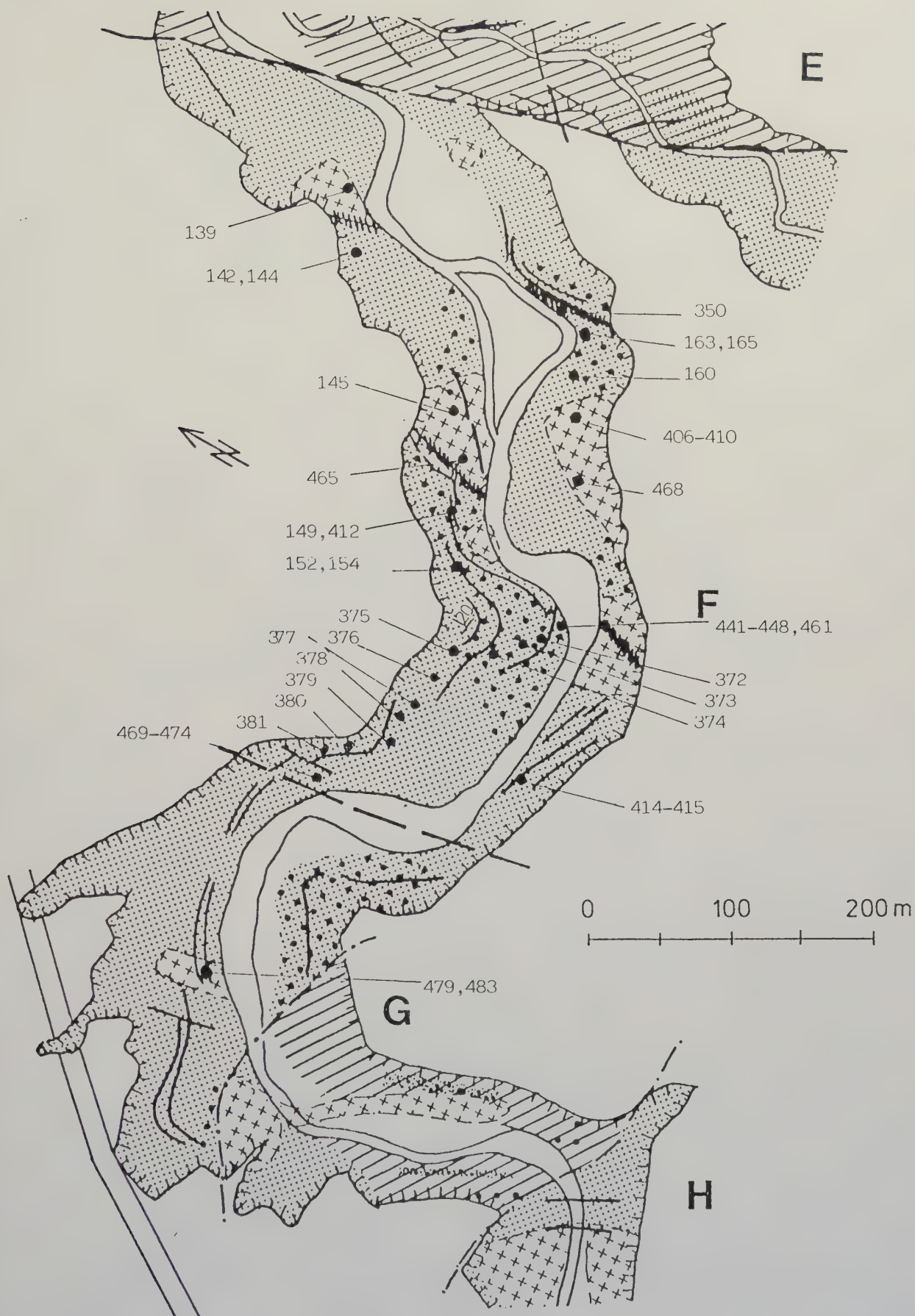


Fig. 2.2e. Detailed geologic map of unit F.

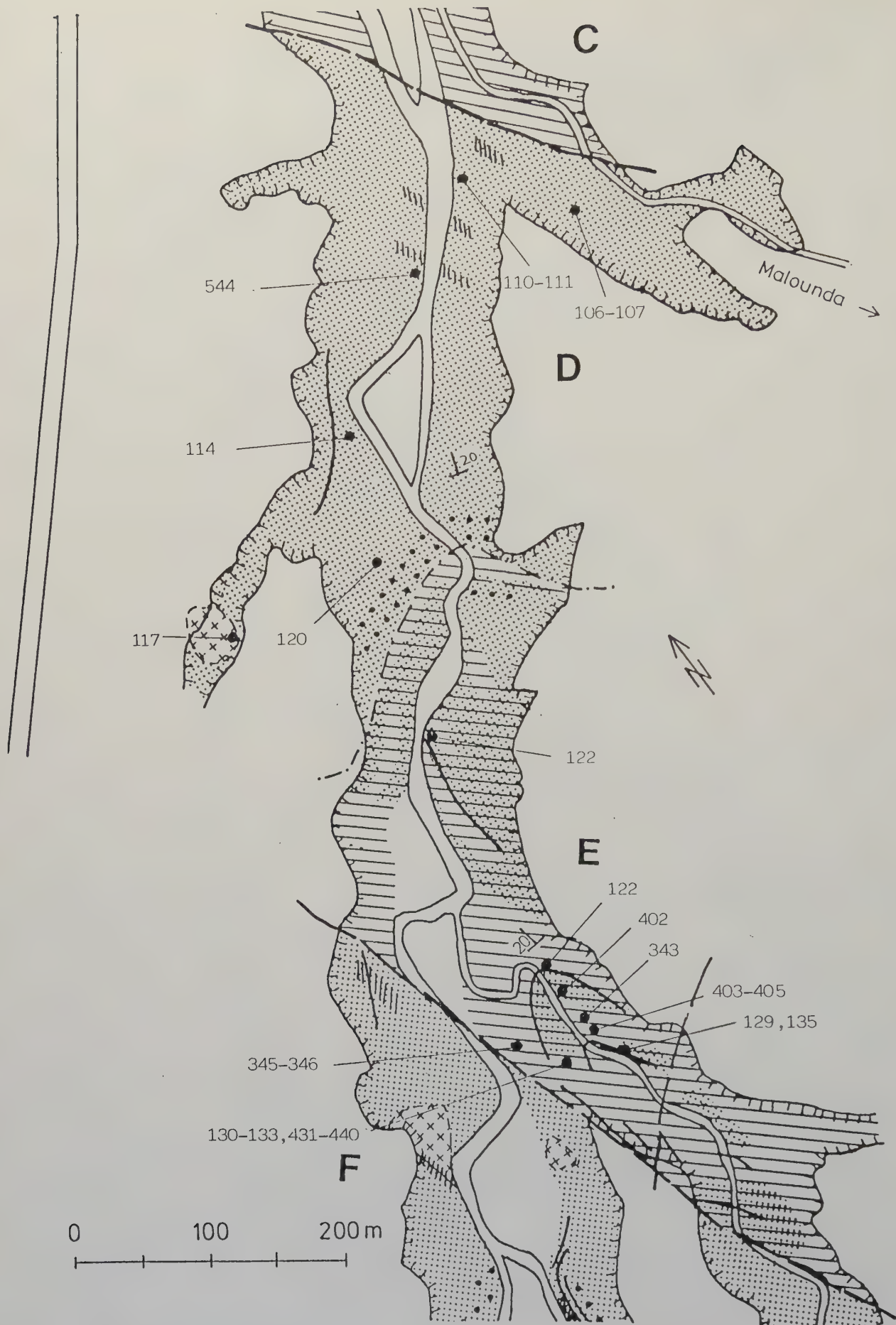


Fig. 2.2f. Detailed geologic map of units D and E.

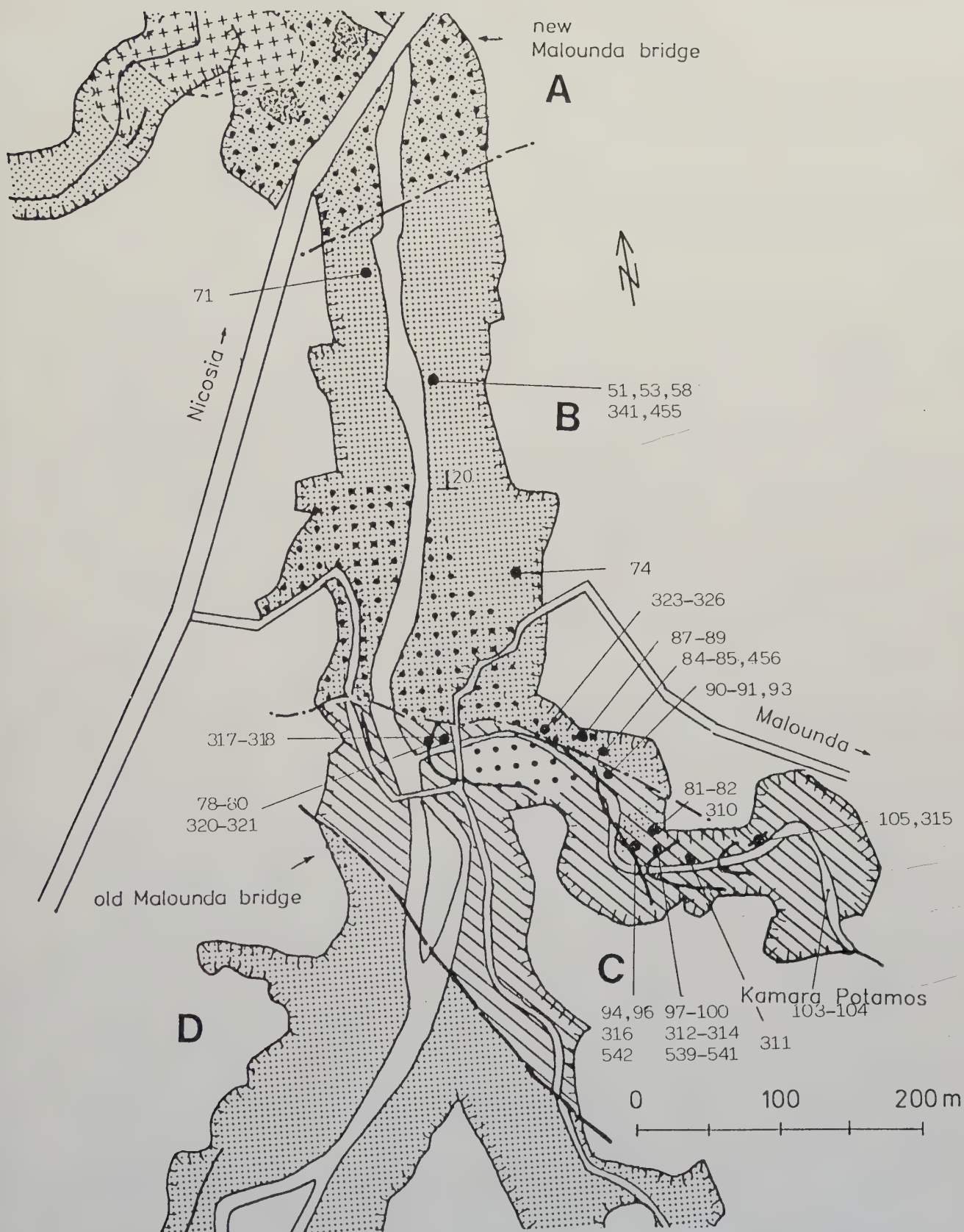


Fig. 2.2g. Detailed geologic map of units B and C.

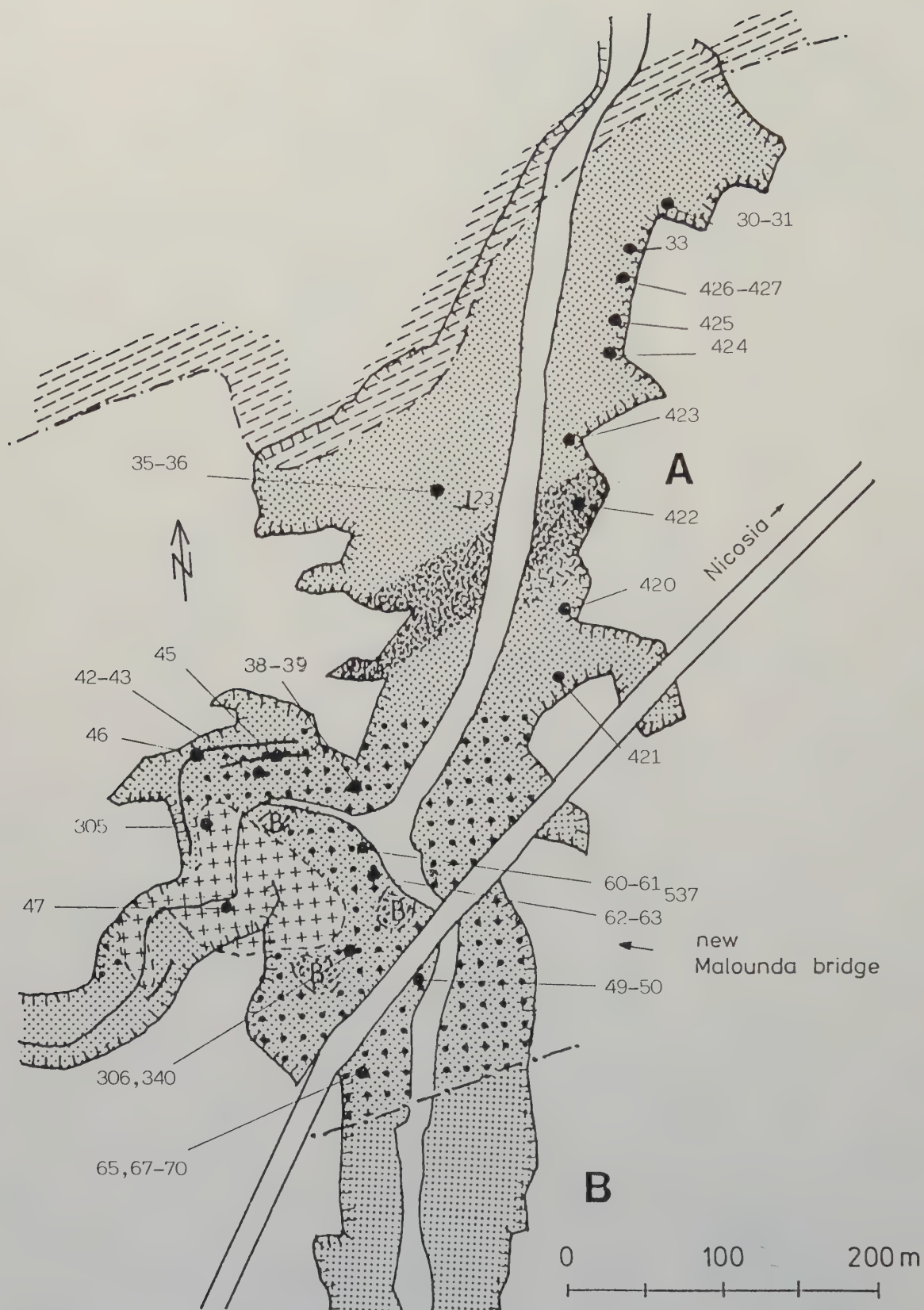


Fig. 2.2h. Detailed geologic map of unit A.

vesicles (2 to 3 mm) occurring in sheets parallel to the top margin. Towards the center of the pillow, the vesicle content and their size decrease. Radial jointing is more pronounced in the lower part of the pillow, due to the smaller number of vesicles. In addition to round vesicles, pipe vesicle (perpendicular to the lower pillow margin) are commonly found. Their sizes range up to 20 by 40 mm and are mostly around 10 by 20 mm. The pillow base is fine grained and vesicular. A quenched margin, 0.5 to 1 cm wide, forms the base of the pillow.

Pillow shapes in the Akaki River section are circular to elongated, sometimes folded-in margins or lobate protrusions and jigsaw puzzle shapes occur. The shapes are very uniform over a large area, e.g. several hundred meters, but in some places, they change within few tens of meters. The shape of the pillow tube depends on the topography, and is highly variable. On flat terrain, tubes often curve and interlayer with each other to form complex patterns. This is the case for most of the pillow lavas in the Akaki River section. On steeper slopes, pillow tubes tend to be rather straight and short, but variable in thickness, and are associated with abundant hyaloclastite and extrusive breccia (see unit K). Pillows are closely packed, or, less often, have interstices filled with glass shards, spalled-off pillow margins, and/or miniature pillows. The diameter of the pillows is variable, ranging from 0.1 to 0.5 m (small pillows), 0.5 to 1.5 m (average sized pillows) and 1.5 to 2.5 m (large pillows). Gradual increase in diameter over an area or stratigraphic interval of several hundred meters were observed, but in some places, drastic changes within a few meters occur, e.g. at boundaries of stratigraphic units. Areas consisting of pillow lavas in the Akaki section may be up to 800 m long. Pillow lavas occur either in distinct pillow lava units (such as unit A, B, D, F, H, J, L,) or they are in minor amounts associated with sheet flows (units C, E, G, I, K,). They make up about 50% of volcanics in the section.

2.2.2 LARGE IRREGULAR BODIES AND LARGE TUBES

2.2.2.1 LARGE IRREGULAR BODIES

Large, coarse grained rock bodies, several tens of meters in diameter were first described from the Akaki River section by Bear (1960). Bear (1960) interpreted them as intrusive plugs, emplaced



Fig. 2.3. Large irregular body (b) and adjacent large tubes (t), interlayered with pillows (p). Two sills (s) crosscut the extrusives. Unit F.

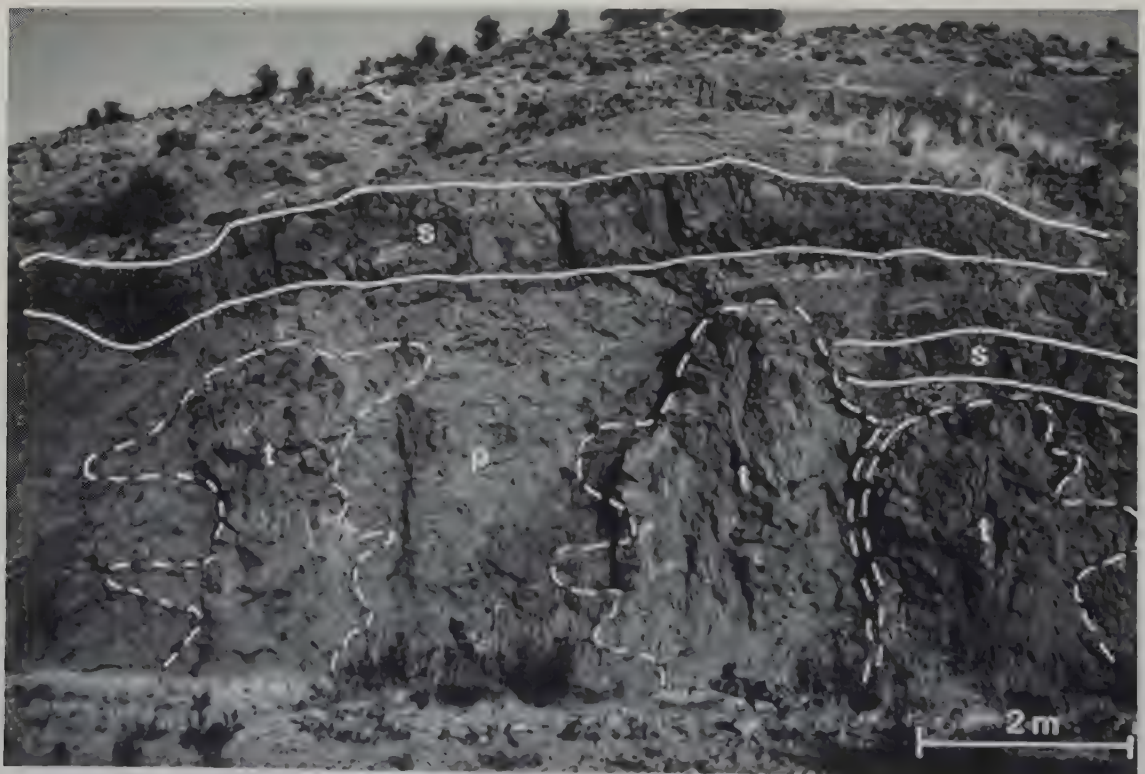


Fig. 2.4. Vertical large tubes (t) interlayering with pillow lavas (p), crosscut by a sill (s), unit F.

after the formation of extrusives. They are described here, because they are spatially and genetically related to the pillow lavas.

These large bodies are coarse grained, vesicular and have irregular outlines (Fig. 2.3). They show columnar jointing, but the large columns are not very distinct because of the coarse grain size and the high vesicle content. Columnar jointing to the sides and top of the body is also radial, perpendicular to the cooling surface. Vesicle sheets are common in the columnar part, spaced several centimeters apart. They become accentuated with weathering and the body may develop a secondary layered appearance, although no compositional layering is present. They are surrounded by pillow lavas and larger tubes. The bodies reach a size up to 40 m high and 150 m wide. They show no intrusive contacts and, in places, conformably overlie pillow lavas with a pillowed base and quenched margins towards their base (e.g. unit F). Lateral and upward terminations of these bodies can be pillows (unit H), or they branch into large tubes (unit F). These bodies often occur in groups. Large irregular bodies are more common in the top of the section, namely in units A, D, F, and H.

2.2.2.2 LARGE TUBES

Large tubes form the lateral and upward continuation of the large irregular bodies (Fig. 2.4). These tubes may be vertical or horizontal: the vertical ones usually are circular in cross section; whereas the horizontal ones are circular or have elongated flat outlines. The shapes are similar to those in pillow lavas, but larger. Lateral extensions of the tubes are normal sized pillow lavas (Fig. 2.4). The diameter of the tubes averages 4 to 5 m, but can reach up to 10 m. The tube length is usually around 8 to 10 m, sometimes up to 40 m. Large tubes occur throughout the section, but are more common in the upper two thirds of it.

Typical examples of large tubes and large irregular bodies are found in unit F. The large tubes are of the vertical type (Fig. 2.4), and have pillowed margins, with glassy margins of about 0.5 to 1 cm thickness. The pillowed "branches" of the large tubes are interlayered with separate smaller pillows, both having quenched margins. Towards the interior zone of the large tubes, the rock is slightly coarser grained, and shows radial jointing. Vesicle sheets, perpendicular to

the columns, may be present and are spaced several centimeters apart. The vesicle size is about 3 to 4 mm, some are up to 7 mm in diameter. The central part is again coarser grained and vesicles are evenly distributed. This zone does not show columnar jointing and is usually not resistant to weathering.

2.2.2.3 FORMATION OF LARGE IRREGULAR BODIES AND LARGE TUBES

In order to interpret the constructional processes operating in the genesis of the extrusive series, it is important to establish the field relations of the irregular bodies and large tubes. Bear (1960) interpreted them as intrusives formed late in the evolutionary history of the extrusive section. Characteristics of intrusive rocks are: crosscutting relationships with pre-existing extrusive or intrusive rocks, apophyses of dike material in cracks of the wall rocks. All

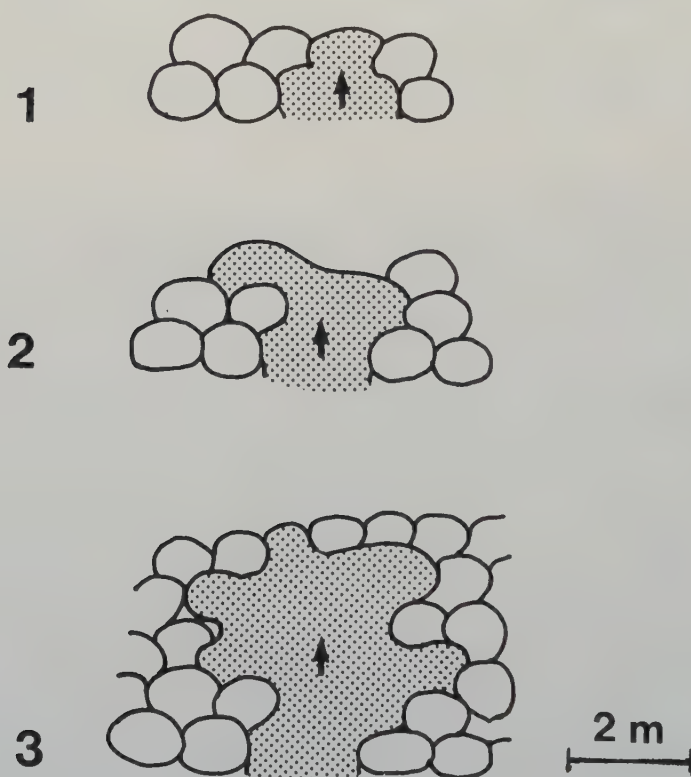


Fig. 2.5. Formation of large tubes (stippled) interlayering with pillow lavas. 1. During the eruption of pillow lavas one of the pillows expands and begins to form a large tube. 2. Continuous eruption feeds both the large tube and the adjacent pillows. The large tube has lateral support from pillows and grows vertically. 3. The lava supply decreases, pillows are formed and overlie the large tube.

these characteristics can be observed on small dikes and sills. They should be much more pronounced and obvious in large intrusives. However, none of these characteristics were found in or associated with the large irregular bodies or the large tubes. All contacts are purely of an extrusive nature, e.g. they conformably overlie pillow lavas and have a pillowed base. There is a continuous textural gradation between large irregular bodies, large tubes and pillows; i.e. no chilled contacts are observed and the grain size variation is gradual. Large tubes and the surrounding interlocking pillows are quenched against each other, so that both had to grow simultaneously. To grow vertically, both the large tube and the pillows had to support each other, otherwise neither the large tube nor the pillows would have been stable. Fig. 2.5 shows the formation of large tubes with adjacent pillow lavas.

2.2.3 SHEET FLOWS

Early observations suggested that the bulk of recent oceanic volcanics consists of pillow lavas (Ballard et al., 1975, Moore, 1975). However, sheet flows are also an important constituent of oceanic crust, as they make up to 30% of the recovered volcanics in drill cores from the Atlantic ocean floor (Robinson et al, 1980). They were described much later than pillow lavas (Lonsdale, 1977, Ballard et al., 1979). Sheet flows on the present day ocean floor show flat surfaces and large lateral extents (Ballard et al., 1979). They are interpreted to form at higher eruption rates than pillow lavas, when the lava supply is too large to form pillows (Ballard et al., 1979).

Sheet flows were also recognized in the Akaki River section (Schmincke et al., 1983). They may be up to several hundred meters long, several tens of meters wide, and up to 12 m thick. Two major types (thick and thin sheet flows) with a more or less regular inner structure can be distinguished, and between these, all transitions are possible. Thick sheet flows (Fig. 2.6) are ponded against fault scarps or pillow mounds; they are tongue-shaped and fill a topographic depression. They may be up to 12 m thick, and 30 to 40 m wide and are usually less than 100 m long. They show a regular inner structure with large basal columns, a massive upper part, and an even, horizontal top. This type of sheet flow is common in the upper part of the section, in units C and E. Thin sheet flows (Fig. 2.7) with large lateral extents



Fig. 2.6. Thick sheet flow (unit E). Note irregular massive upper part (m) and basal columns (c).



Fig. 2.7. Thin sheet flow (unit I). Note columnar base, backweathering center, and massive upper part (sf: sheet flow, d: dike)

up to several 100 m are not ponded, commonly up to 3 to 6 m thick, locally up to 8 m. The internal structure is less regular than in the thick sheet flows, but basal columns are usually present. Their bases and tops may be irregular, where overlying irregular topography. Thin sheet flows are more common in the lower part of the section, in unit G, I and K. Sheet flow are less abundant than pillow lavas, they make up about 30% volume of the sequence. They occur mostly as distinct lithologic units, which consist dominantly of sheet flows and contain only a minor amount of pillow lavas (units C, E, G, I, K).

The internal structure of the sheet flow depends on the topography and the underlying material. Usually, a sheet flow can be divided into three major zones:

1. Lower collonade with a quenched base, sometimes with a basal breccia. This zone usually makes up about one third of the thickness of the sheet flow.
2. The central massive part, making up about two thirds of the flow thickness. This zone may contain short, irregular columns and the vesicle size increases dramatically towards the top. In general, the vesicles are smaller (1 to 3 cm) in thin, unponded sheet flows than they are in thick, ponded flows (up to 10 cm).
3. The top zone may consist of hyaloclastite breccia. The thickness of this layer is variable, only a few tens of centimeters.

The contacts of sheet flows are variable, depending on the topography and the nature of the underlying rocks. If sheet flows overly pillows, the flows may show a pillowed base with chilled glassy margins (e.g. in unit E). Thick, basal breccia, also glassy, occur in places where sheet flows moved over hyaloclastite or breccia at the top of a previous sheet flow (see unit G). These breccias may be incorporated into the basal part of the sheet flow during flow and cause irregularities in the otherwise massive part of the flow. The tops of sheet flows vary, depending on the sheet flow type. For thick sheet flows, they are mostly even and horizontal, thin sheet flows may have tops that are irregular at their base, because they have a smaller thickness and cool more rapidly. Sheet flows always have a layer of hyaloclastite at the top. Lateral terminations, especially of thick sheet flows, are variable. Some are ponded against fault scarps of pillow mounds, the flow fronts of others end abruptly or form

transitions into pillows budded from the sheet flow front.

Three sheet flows will be described in detail, one from unit C, typical for the upper part of the section; one from unit I, typical for the lower part of the section; and a special case, a hyaloclastite-rich sheet flow of unit G.

1. The ponded sheet flow in the Kamara Potamos (unit C) (Fig. 2.2g) is 6 m thick and at least 200 m wide. Overlying an older sheet flow with a horizontal top, the base and top of this sheet flow is also horizontal. The internal structure is regular and is divided up into three parts, the lower colonnade, the central massive part, and the top zone consisting of hyaloclastite. A thin glassy breccia forms the base of the flow, at about 2 cm follows the lower collonade with a thickness of 0.8 to 1 m, the diameter of the regular straight columns being 0.2 to 0.4 m. Up to 10 cm above the base, there are only a few vesicles, less than 5 mm in diameter. Some vesicles (about 3 mm in diameter) occur in sheets at about 30 cm height, spaced 4 to 6 cm apart. Pipe vesicles and single, larger vesicles up to 8 mm in diameter may occur between the vesicle sheets. 30 cm above the base, the pipe vesicles disappear, and only vesicle sheets with round vesicles between these sheets are present.

Columnar joints are barely visible in the coarser grained, vesicular massive zones. Vesicles are small, abundant and evenly distributed. This zone is followed by a zone more resistant to weathering with short irregular columns (50 cm in diameter) without parallel jointing. This part of the sheet flow is finer grained and has large arched vesicles of 8 to 10 cm diameter. Small vesicles are round and less abundant in the central zone of the flow. Above the massive part of the sheet flow, there is a transition zone into a rubbly unwelded hyaloclastitic layer of 30 cm which forms the top part of the sheet flow.

2. The sheet flows of unit I (Fig. 2.7) are variable in thickness because they advanced over very irregular topography. Most are between 4 and 6 m, some are up to 8 m thick, in places where they are ponded. Above a sharp quenched contact at the base follow the basal columns with about 2 m thickness. The rock is fine grained and vesicles (up to

5 mm) are evenly distributed. Smaller vesicles form thin vesicle sheets, spaced about 6 cm apart. Single vesicles range up to 1 cm in diameter. The massive central part (1.5 m thick) has less pronounced columnar jointing, and shows a transition upwards into a highly vesicular zone of 0.8 to 1.2 m. Vesicles in this zone are up to 2 cm in diameter, often arched and have irregular outlines. The vesicles are grouped in clouds, and vesicle sheets are absent. Some irregular columns occur in this zone, spaced 30 to 50 cm apart, with length of 50 to 60 cm. Above this lies a fine grained, highly vesicular zone, with a layered appearance, although no chilled contacts are present. Vesicle sizes are up to 6 mm. The top of the sheet flow consists of a layer of hyaloclastite.

3. The hyaloclastite-rich sheet flow of unit G differs significantly in internal structure and boundary configuration (Fig. 2.8) from the normal thick and thin sheet flows. It has a very irregular, but sharp lower boundary. The central part of this sheet flow consists of zones of vesicular lava adjacent to vesicle-free zones. It is suggested that vesicular, still partially molten fragments of lava were chilled and welded together. The fine-grained fragments are commonly about 10 cm long (in some cases up to 20 cm), and 4 to 6 cm wide. Within the

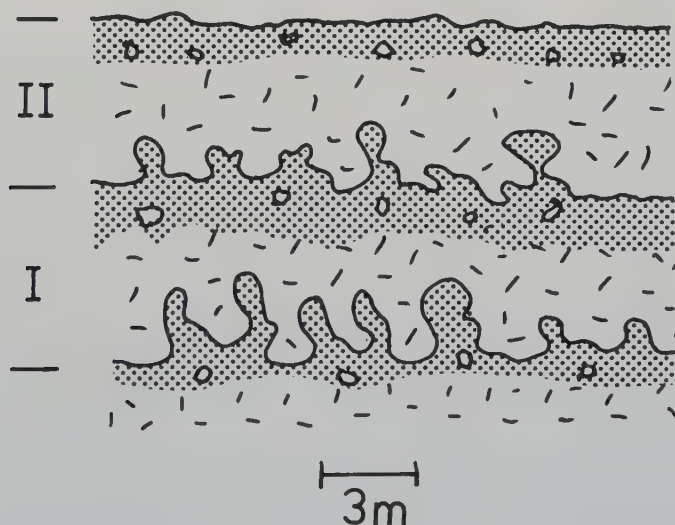


Fig. 2.8. Schematic cross section of hyaloclastite-rich sheet flows (unit G). The lower, massive part of the sheet flow (I) is overlain by the hyaloclastite-rich top zone (II). The flow incorporates the underlying hyaloclastite into its base as it advances.

fragments, vesicles are up to 6 mm but average about 2 mm in diameter. They are elongated and oriented subparallel to the rims of the drops. However, the elongated fragments themselves show no parallel orientation. Flow striations between the fragments are common. Small, celadonite-rich brecciated zones with maximum width of 40 cm occur between the vesicular fragments.

In some places, no separate pieces can be recognized, the rock is completely vesicular, but still shows areas of elongated, oriented vesicles. Columnar jointing is absent throughout the massive zone of this sheet flow. Vesicles are more abundant in this flow than in others, but they are very small compared to those in other sheet flows. This zone gradually changes upwards into a hyaloclastite of 3 to 4 m thickness. The massive rock branches into smaller massive areas, interlayered with hyaloclastite; further upwards massive pieces are isolated in the hyaloclastite, followed by a zone made up only of hyaloclastite. The massive rock fragments show chilled margins in contact with hyaloclastite. The hyaloclastite consists of glassy "nodules" and fragments, 2 to 3 cm in diameter, and small glassy fragments of less than 0.5 cm in diameter.

It is suggested that this flow formed during a spatter eruption. Spatter formed the fragments that were successively welded together while still plastic, and then this mass advanced as sheet flow. When it moved over hyaloclastite from the underlying older sheet flow, it incorporated this into its base and center.

2.2.4 DIKES AND SILLS

Dikes and sills crosscut extrusive and intrusive rocks (Fig.2.9). An important characteristic of dikes and sills are the chilled, commonly glassy margins on both sides of the intrusive rock. Other characteristics are the symmetric inner structure, e.g. columnar jointing on both sides and their constant thickness. They occur singly or in groups. Sills, and sill-dike transitions are common in the upper part, whereas dikes, often as multiple intrusions, are more common in the lower part of the section, where extrusive rocks decrease in abundance towards the sheeted dike complex. The intrusives constitute about 9 % of the volcanics of the section.



Fig. 2.9. Irregular pillow lavas (p), extrusive breccias and hyaloclastites (hy) of unit L, crosscut by multiple dikes (d).

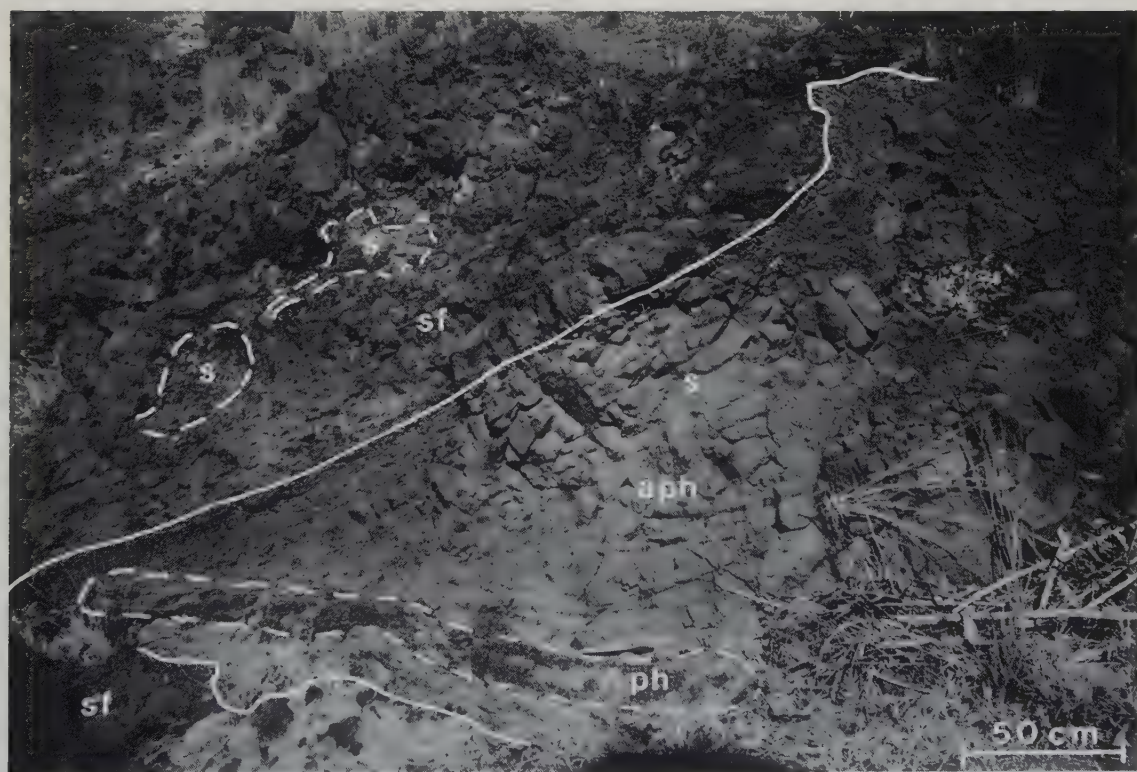


Fig. 2.10. Phenocryst-rich sill (s), intruded into sheet flows (sf) of unit C (Kamara Potamos). A quenched margin is present on both sides of the sill. The phenocryst-rich part (ph) is restricted to a thin zone at the base of the sill. The thickness of the upper, aphyric part (aph) of the sill is variable.

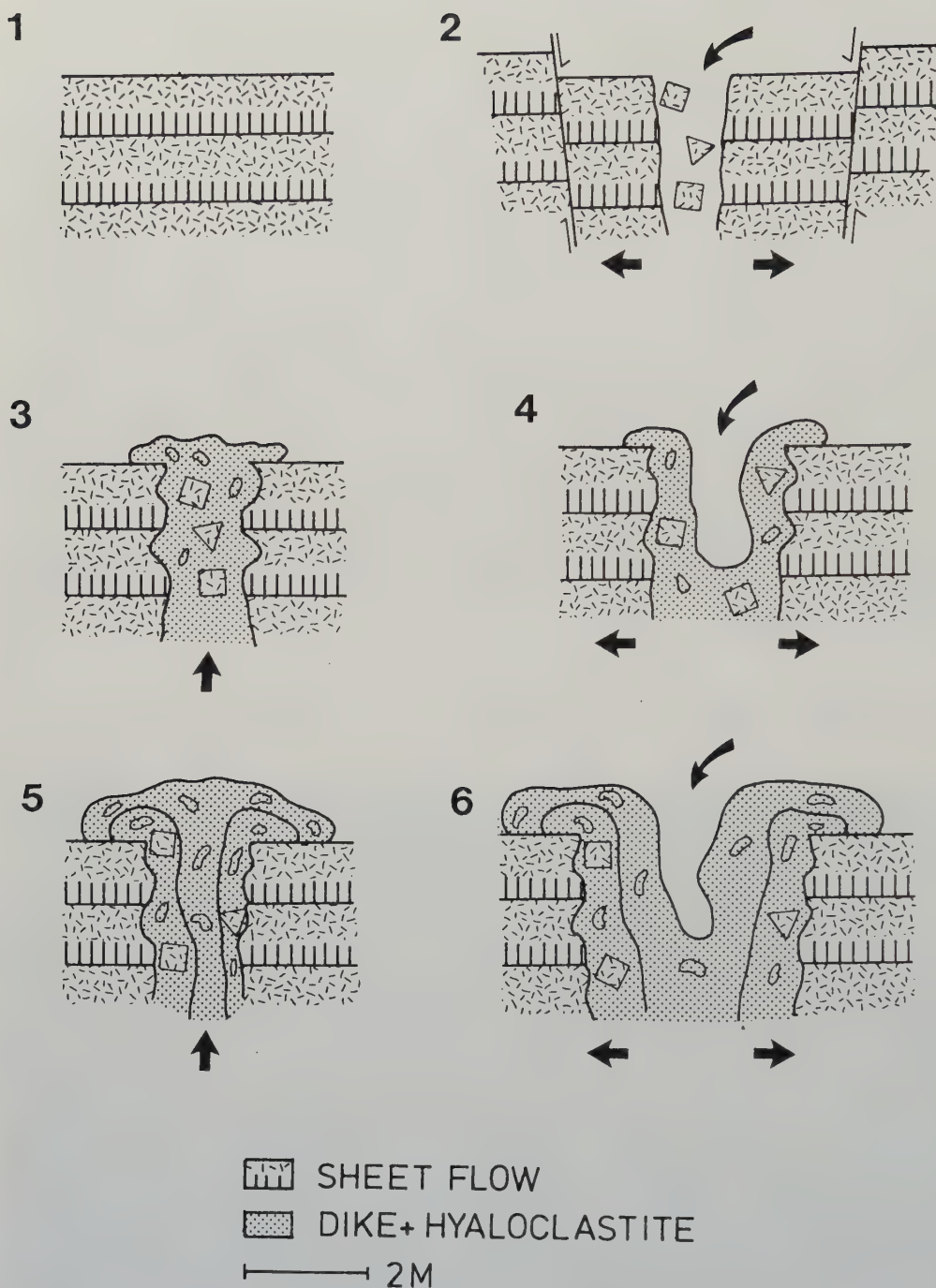


Fig. 2.11. Evolution of a hyaloclastite-rich feeder dike as in unit C. 1. Sheet flows of unit C form; 2. extension and faulting, blocks of sheet flow material fall into the newly formed fissure; 3. intrusion and eruption of the feeder dike enclose sheet flow blocks; 4. new extension and/or drop of lava level with formation of hyaloclastite, 5. new intrusion - extrusion; 6. extension and/or drop of lava level with formation of hyaloclastite.

Apophyses into the host rock are common. Sills and dikes have a symmetrical structure, from the quenched margins towards the coarser grained center. The host rocks of dikes and sills commonly show a reddish color, due to contact heating. These oxidized zones are more resistant to weathering than the dike or sill itself. Flow marks on the wall rocks indicate the flow direction of the sill or dike.

Two examples of intrusives will be described, a phenocryst-rich sill from unit C, and a hyaloclastite-rich feeder dike from unit C.

1. The phenocryst-rich sill from the Kamara Potamos (unit C) (Fig. 2.10) intrudes a sheet flow breccia and has small apophyses, reaching about 8 cm upwards and downwards into the wall rock. The apophyses are mostly glassy (0.5 to 1 cm thick) or when larger (few centimeters), very fine grained with a glassy margin. The number of apophyses depends on the number of cracks in the wall rock. The sill is aphyric in an interval up to 10 cm above the base; then follows a zone with few phenocrysts, then a zone (30 cm thick) with densely packed phenocrysts of olivine, clinopyroxene, and spinel, oriented parallel to the base of the sill. Above that, the number of phenocrysts decreases rapidly within a few centimeters, then follows the aphyric part of the sill. The phenocryst-rich zone is only about 2 m wide, and to the side, the sill is completely aphyric. Vesicles are evenly distributed through the sill, their size slightly increases from the rim (1 mm) towards the center of the sill (3 mm). The sill shows columnar jointing in the aphyric part, on both sides, where the rock is fine grained. Columns are absent in the phenocryst-rich part.

2. The feeder dike in the Kamara Potamos (unit C) is a special case, because it is partially intrusive into the sheet flows of unit C, and partially extrusive, because it feeds pillow lavas of the overlying unit B (Fig. 2.11). The dike encloses parts of the sheet flows as blocks in the dike material (Fig. 2.11). Furthermore, the dike contains abundant hyaloclastite and small drops of dike material, chilled against the hyaloclastite. The dike branches several times and rejoins itself further up or to the side.

These unusual features are interpreted as follows:

1. The sheet flows of unit C were fissured and some sheet flow material dropped into the fissure.

2. The dike intruded into these fissures and enclosed the sheet flow blocks in dike material.
3. When the dike reached the sea-floor, it started to erupt pillow lavas of unit B.
4. New extension and/or a variation in the lava level formed hyaloclastite and chilled margins on larger melt drops.
5. A larger pulse of intrusion/extrusion produced more hyaloclastite and pillows.

2.2.5 EXTRUSIVE BRECCIA AND HYALOCLASTITE

In the Akaki River section, the extrusive breccia bodies range from several tens of centimeters to layers of 6 to 8 m thickness, extending laterally over up to 200 m (unit L). They occur in interstices between pillow lavas, with an extent of 30 to 40 cm, and within open fissure eruption products (unit C). They are also present as distinct layers within a lithologic unit, e.g. in unit A. They are common throughout the whole section, and are more abundant in the lower part of the section, in units L, K, J, I, and G. Pure hyaloclastites without larger components occur as top layers of sheet flows, and are about 30 cm thick (in some cases up to 4 m thick, e.g. unit G).

Components of the extrusive breccia in order of decreasing abundance are (Fig. 2.12) (see also Table 2.1):

1. Miniature pillows with chilled margins, 2 to 5 cm in diameter, with few small vesicles. Small lava drops are often entirely glassy.
2. Larger, irregular pillows, often elongated, with folded-in margins, 5 to 20 cm long.
3. Very flat pillows, up to 60 cm long, 4 cm high, with multiple spalled-off margins. These pillows may be fractured, with small glassy fragments in the fractures, but the large pieces are still nearly coherent.
4. Fragments of glassy pillow margins, spalled-off from pillows or miniature pillows. These fragments have a rectangular shape, and they are 0.5 to 3 cm long. Their orientation is usually parallel to the pillow rim they originated from, or less often, random. This component is the major constituent of pillow interstices and sheet flow tops.
5. Intact larger pillows, up to 50 cm in diameter. Folded-in glassy margins are common.



Fig. 2.12. Extrusive breccia, unit K, formed by granulation of hot lava. Glass is partly altered to clay minerals (brown). Larger lava drops are fine grained with quenched glassy margins.

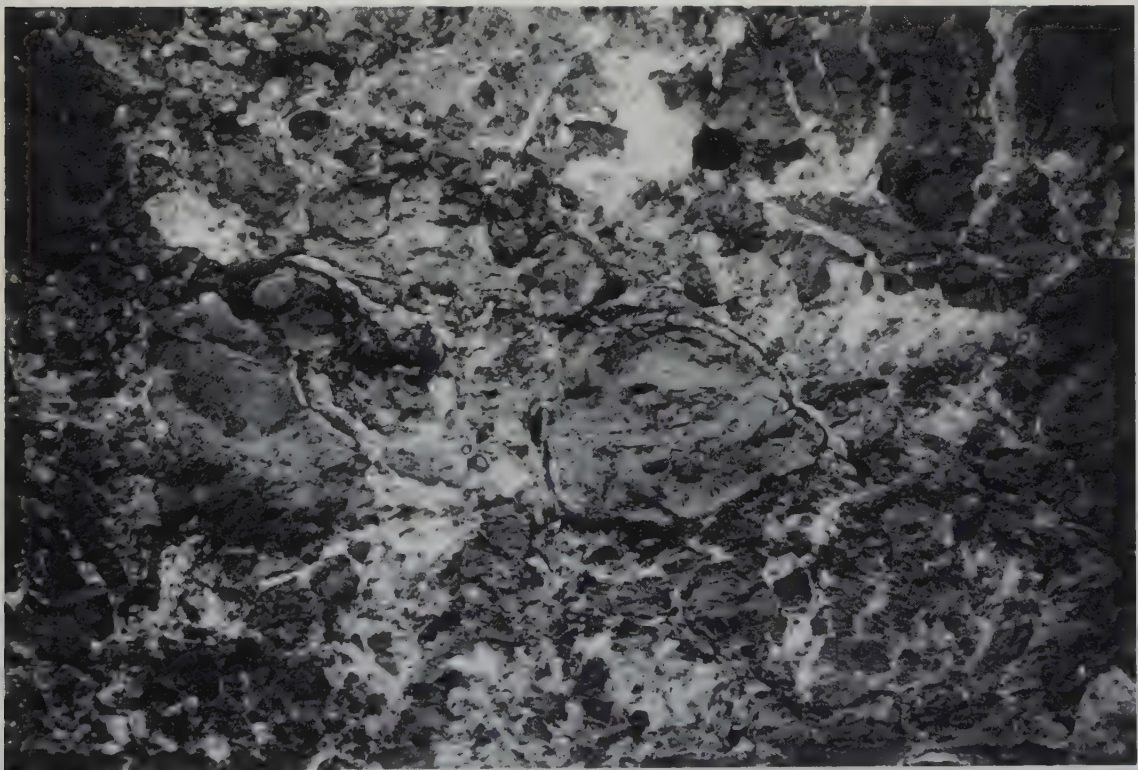


Fig. 2.13. Talus breccia, unit A, formed by erosion. Pillow fragments are surrounded by a matrix of small lava fragments and pelagic sediment.

6. Fragments of pillows with only partly quenched margins. These range in size from 3 to 10 cm, and the majority is around 3 to 4 cm in diameter.

The matrix of extrusive breccia consists of hyaloclastite, i.e. small, angular or round glassy clasts. The breccias may be layered, grading is not common.

This breccia type forms by irregular spattering of small quantities of lava (Lonsdale & Batiza, 1980, Fisher, 1984, Fisher & Schmincke, 1984) at a low eruption rate. The lava granulates at the contact with water. Larger lava drops form miniature pillows; smaller droplets form glassy fragments. Layers of hyaloclastites on top of sheet flows and between pillows are caused by the movements of the flow and spalling-off of the freshly formed, rigid quenched margins. Several features indicate that these breccias form in situ, and have not been transported over a large distance; only a small amount of fine grained material is present, small fragments are angular, and the glassy rims of miniature pillows are preserved.

2.2.6 TALUS BRECCIA

Talus breccia consists of randomly orientated, poorly sorted fragments in a fine to medium grained matrix (Table 2.1). No layering is present. Bodies of this type of breccia are up to 15 m thick, and 20 to 30 m wide extent in lenticular shaped bodies (Fig. 2.13). This type of breccia occurs only at the top of the section, in units A (Fig. 2.2.h).

Components of talus breccia in order of decreasing abundance are:

1. Angular fragments of pillows are often wedge shaped, some have a chilled margin on one side. These fragments were derived from pillows larger than 1 m in diameter. The fragment size is mostly around 10 to 30 cm, but may range up to 60 cm. The smallest fragments are 0.5 to 3 cm in diameter.
2. Single, small intact pillows without context, some are upside down.
3. Larger fractured pillows with partly dislocated or missing fragments.
4. Parts of an extrusive breccia may be incorporated as components in a talus breccia.

Table 2.1. Characteristics of extrusive and talus breccia

	extrusive breccia	talus breccia
<u>components</u>		
"Lava drops" with chilled margins (miniature pillows)	common	rare
partly chilled, pie-segment-shaped pillow fragments	rare	abundant
fragments of glassy pillow margins	abundant	very rare
<u>matrix</u>		
hyaloclastite	abundant	rare
small fragments of all components	rare	abundant
minute particles of pelagic sediment	absent	abundant
<u>texture</u>		
layering	usually absent	absent
sorting	none	none
orientation of components	larger components right side up	random
<u>formation</u>	formed by granulation of hot lava or by spalling of quenched rims of sheet flows and pillows	formed by erosion, at low temperatures; mixing of components and matrix by slumping
<u>transport</u>	almost none essentially in situ	not transported far, but mixed well; no orientation of components

The matrix of talus breccias consists of small fragments of all the types described above, smaller than 1 cm in diameter, and sediment particles, consisting of lime mud, derived from the overlying pelagic sediment.

This type of breccia is interpreted to have formed in a different way than the extrusive breccia. Glassy margins are never complete on the fragments, and the the matrix is not glassy. All fragments were formed at low temperatures, no hot lava was present. If pillows are complete, they are completely dislocated from their context. This breccia is fairly well, but not thoroughly mixed, and no layering and/or sorting is present. It is probably formed by erosion of different types of rocks at the surface of a pillow mound (exposed to the sea-floor for a certain amount of time), these then slid and slumped into a topographic depression. Lime mud was incorporated into the breccia as matrix.

2.2.7 SUMMARY OF CHARACTERISTICS OF LITHOLOGIC TYPES

A summary of the characteristics of the lithologic types is given in Table 2.2.

2.2.7.1 CONTACT RELATIONSHIPS

All extrusive lithological types have depositional contacts, and quenched margins at top, side and base. Pillow lavas, large tubes and large irregular bodies have pillowed quenched margins. Sheet flows may have a pillowed margin or a thin breccia at the base, and always feature a hyaloclastite layer on the top. The lateral termination may be formed by pillows. Intrusive rocks crosscut the pre-existing lithology, e.g. pillow lavas. This caused quenching and injection of the intrusive melt into the cold preexisting rock. The host rocks of sills and dikes are often oxidized and more resistant to weathering than the extrusive rock. Extrusive and talus breccias always have depositional contacts. Extrusive breccia formed at the presence of hot lava; lava granulated in situ to hyaloclastite and formed miniature pillows that are quenched on all sides. Components are oriented with their right side up. In contrast, components of talus breccia components are fragments formed by fracturing at low temperatures, e.g. by erosion on the sea-floor. Components and matrix are not oriented, and the breccia formed by slumping and sliding.

2.2.7.2 INTERNAL STRUCTURE

The internal structure of a lithologic type depends on its cooling history. Pillows show radial jointing in their vesicle-poor half, whereas the vesicle-rich upper half is usually not jointed. Large

Table 2.2. Summary of characteristics of lithologic types

	pillow lava		large tubes		large irregular bodies		sheet flows		sills & dikes	
<u>contacts</u>	extrusive depositional		extrusive depositional		extrusive depositional		extrusive depositional		intrusive	
top	quenched margin		quenched margin branch into pillows		quenched margin branch into tubes and pillows		quenched margin top hyaloclastite layer		quenched margin apophyses	
lateral	quenched margin		quenched margin branch into pillows		quenched margin branch into tubes and pillows		quenched margin some branch into pillows		quenched margin apophyses	
base	quenched margin		quenched margin		quenched margin		quenched margin breccias		quenched margin apophyses	
<u>internal structure</u>										
top	fine grained		fine grained		fine grained		fine grained		fine grained	
	very vesicular vesicles up to 5 mm		vesicular vesicles up to 5 mm		vesicular vesicles up to 5 mm		very vesicular vesicles up to 10 cm		vesicular vesicles up to 3 mm	
	columnar jointing not pronounced		columnar jointing not pronounced		columnar jointing not pronounced		no columnar jointing		columnar, parallel jointing	
center	fine grained vesicular		medium grained vesicular		coarse grained		fine to medium grained		fine to medium grained	
			small vesicles evenly distributed		vesicular small vesicles evenly distributed		vesicular small vesicles evenly distributed		very vesicular small to medium sized ves. evenly distributed	
	columnar jointing visible		no columnar jointing		columnar jointing not pronounced		columnar jointing irregular, massive		columnar jointing not pronounced	
base	fine grained		fine grained		fine grained		fine grained		fine grained	
	sparsely vesicular vesicles up to 3 mm		sparsely vesicular vesicles up to 3 mm		sparsely vesicular vesicles up to 3 mm		sparsely vesicular vesicles up to 4 mm		vesicular vesicles up to 3 mm	
	columnar, radial jointing		columnar, radial jointing		columnar, parallel jointing		columnar, parallel jointing		columnar, parallel jointing	
<u>color</u>	grey to yellow brown		grey to yellow brown		grey to yellow brown		grey - green		grey to yellow brown	
<u>alteration</u>	zeolites		zeolites		zeolites celadonite		celadonite, zeolites chalcedony		zeolites, chalcedony red oxidation halos on host rock	
<u>occurrence</u>	throughout section		throughout section		more common in upper two thirds of section		throughout section		dikes more common in lower part, sills more in upper part	

tubes and large irregular bodies have pillowed rims and towards the center radial columns occur perpendicular to the cooling surface. The central parts of these lithologic types are more vesicular, coarser grained and show no columnar jointing.

Sheet flows are usually fine grained, show an asymmetric inner structure, and can be divided onto three major zones, the large regular basal columns, central massive part, sometimes with irregular columns, and top hyaloclastites. The basal columns usually make up one third of the thickness of the sheet flow. In this zone small pipe vesicles and vesicle sheets may be present. In the central massive part, vesicles are very large and irregular, up to 10 cm in diameter.

Dikes and sills have a symmetric inner structure. On both sides, they have parallel columns perpendicular to the cooling surface, and have quenched margins as contacts. The central parts of dikes and sills are coarser grained and more vesicular, and are often not jointed. The inner structure of large sills and large lava bodies may be similar, and they may not always be distinguishable; if the contacts to the surrounding pillow lavas are not well exposed.

2.2.7.3 ALTERATION

Vesicles in pillow lavas, large lava bodies and large lava tubes show the same alteration pattern, and are often filled with smectite, calcite, analcime, phillipsite, nathrolite, gmelinite, and chabazite. These secondary minerals also occur on radial cracks in pillows (Gillis & Robinson, 1985).

The alteration pattern in sheet flows differs from that found in pillow lavas. Vesicles are partly filled with smectite, calcite, green celadonite, clinoptiololite, mordenite, opal-c, opal-ct, chalcedony, and quartz (Gillis & Robinson, 1985).

Secondary minerals in vesicles in dikes are zeolites, smectite, chalcedony and quartz.

2.3 STRATIGRAPHIC UNITS IN THE AKAKI RIVER SECTION

2.3.1 MAPPING TECHNIQUES

Strike and dip of the volcanics along the Akaki River section are rather uniform with ca 90/20°N (Fig. 2.1, 2.2). The section was divided into twelve stratigraphic units, i.e. from unit L at the base through to unit A at the top of the section. Each of these units comprises a large stratigraphic interval of the section, several tens to hundreds of meters in thickness, and consists of volcanics with similar characteristics; e.g. dominantly pillow lavas or dominantly sheet flows. Boundaries between units are drawn where the dominant lithologic type changes; e.g. from only pillow lavas to only sheet flows, or at unconformities; or at tectonic breaks in the section. The stratigraphic units will be described from the base of the section (unit L) to the top of the section (unit A) (Fig. 2.1). The nature of the unit boundaries, the dominant lithologic types and a brief description of the structure are given.

2.3.2 UNIT L (Fig. 2.2a)

The large number of dikes obscures the relationships between the extrusive rocks in the lowest part of the section, therefore no units were distinguished below this point.

Aphyric pillow lavas are the dominant rock type (60%). The remaining 40% are equally divided between extrusive breccias and hyaloclastites, and dikes. The dikes increase towards the base of the unit, in many cases multiple intrusions are observed (Fig. 2.9). Pillow lavas vary in size (1 to 3 m) and shape within this unit. They are interlayered with thick layers (3 to 4 m) of extrusive breccias and hyaloclastite (Fig. 2.2a, 2.9). No major faults are present in this unit. The strike is about 90/20°N. The thickness of the unit is at least 200 m.

2.3.3 UNIT K (Fig. 2.2a,b)

Aphyric sheet flows are the most abundant rock type in this unit (55%). They form an unorganized succession with extrusive breccias and hyaloclastites (20%) and pillow lavas (15%). Dikes make up about 20% of the unit. Sheet flows are all of the thin type, with an irregular base and top, usually about 4 to 6 m thick. Some extend over several



Fig. 2.14. Irregular sheet flows (sf) crosscut by dikes (d), unit K.



Fig. 2.15. Boundary between stratigraphic units C (C), consisting of sheet flows (sf) and pillows (p); and unit B (B), consisting of pillow lavas (p) and large tubes (t) and feeder dike (d), in the Kamara Potamos (see also Fig. 2.2.g). Note the occurrence of the secondary mineral celadonite (ce) in unit B.

100 m, others seem to be restricted to smaller extents (Fig. 2.14). Outcrops are poor in parts of this unit. Pillow lavas are irregular in shape and size. In places, the shape of the pillow lavas (very elongated and broken off), and the association with a large amount of hyaloclastite indicates an originally very steep topography. Extrusive breccias and hyaloclastite occur either as layers between sheet flows (Fig. 2.14), or between pillows. There are also transitions between sheet flows and pillows. Dikes occur in groups, often as multiple dikes, e.g. at the base of the unit (Fig. 2.2.a), or as single intrusions.

There are no major faults in unit K. The dip of the extrusives is in average 20°, but locally dips up to 40° occur. The thickness of this unit is 370 m. The dikes strike about 0-30°/80-90°N.

The boundary to unit J was drawn at the transition zone between sheet flows of unit K and regular pillows of J. This transition zone is a few meters thick.

2.3.4 UNIT J (Fig. 2.2.c)

Aphyric pillow lavas and some large tubes are the dominant lithologic type (80%). Extrusive breccias and hyaloclastites constitute 5% and dikes 15%. Pillow lavas are closely packed and have jigsaw-puzzle shapes with folded-in margins. Diameters of pillows vary between 1 m and 2 m, decreasing towards the top of the unit. Within this pillow unit, layers of large lava tubes up to 6 m in diameter occur. They are found at the base of the unit, and decrease in number towards the top. Dikes, often occurring as multiple intrusions, concentrate in the base of the unit. There are less dikes in this unit than in the lower units K and L.

No major faults occur in unit J, but some smaller ones offset the dikes and sills for 1 to 2 m. The strike of the extrusive volcanics is about 90/20°N. The thickness of this unit is 105 m.

The boundary between unit J and unit I was drawn below the lowermost sheet flow of unit I.

2.3.5 UNIT I (Fig. 2.2c)

Aphyric sheet flows are the dominant lithologic type (60%), pillow lavas constitute 10%, extrusive breccias and hyaloclastite 15%, and dikes and sills 15%. Sheet flows (thin type) (Fig. 2.7) can be followed over several tens of meters. The sheet flows alternate with small amounts of pillows and extrusive breccias. Pillow lavas and extrusive breccias are more abundant in the central part of the unit; whereas sheet flows dominate in the top and basal zone. In the upper part of this unit, sills are more common, whereas the lower part contains more dikes. One phenocryst-rich sill occurs in a large lava body.

This unit contains no major faults; the strike of the extrusives is about 90/20°N. The thickness of the unit is 80 m.

The boundary between the units I and H is marked by an unconformity between sheet flows of unit I and pillows of unit H.

2.3.6 UNIT H (Fig. 2.2d)

Aphyric pillow lavas and some large tubes constitute make up part of this unit (60%); another major constituent is a large irregular body (35%). Few dikes occur (5%). Pillow lavas have round shapes (0.5 to 1 m in diameter), and decrease in size towards the top. The top zones of pillows are very vesicular and weathered. Pillows are the lateral and upward continuations of the large irregular body at the top of the unit, whereas its base is not exposed and may be intrusive or extrusive. A layer of large tubes is present in the lower part of the unit. This unit contains the last multiple dikes, in all overlying units in the section dikes occur only as single intrusions.

No major faults occur in unit H. The strike of the extrusives is 90/18 to 20°N; the thickness of the unit is 75 m.

The pillow lavas at the top of unit H are oxidized, and no fresh glass is present. The boundary to unit G is drawn where the fresher pillows with thick fresh glassy margins of unit G overlie the oxidized ones of unit H.

2.3.7 UNIT G (Fig. 2.2d)

The dominant lithologic types in this unit are aphyric; hyaloclastite-rich sheet flows (55%), pillow lavas (25%), hyaloclastite and extrusive breccia (15%), and dikes (5%). The hyaloclastite-rich sheet flows are those described in detail in section 2.2.3, (Fig. 2.8). They consist of equal parts of extrusive breccias and massive rocks. Pillow lavas under- and overlie the sheet flows and also form lateral extensions of them (W-bank). Pillow lavas are round-shaped, elongated and irregular, with diameters up to 1 m. The top half of the pillows is very vesicular. Pillows of unit G do not show any systematic change in diameter. The glassy rims on the pillows are very thick, up to 4 cm. One large irregular body with intrusive and extrusive characteristics is present in this unit. On the E-bank of the section, it intrudes like a dike into the hyaloclastite-rich sheet flows, whereas on the west side of the river its contact relationships are less clear, there it seems to have a transition into the overlying large tubes of unit F.

No major faults occur in unit G. The strike of the volcanics is 90/20°N; the thickness of this unit is 70 m.

The contact to unit F on the W-side of the river is formed by large tubes overlying the irregular body; whereas on the E-side of the river large tubes and pillows of unit F overlie the hyaloclastite-rich sheet flows of unit G conformably.

2.3.8 UNIT F (Fig.2.2e)

The lithologic types in this unit are aphyric pillow lavas and large tubes (65%), large irregular bodies (30%), and sills (5%). The pillow lavas interlayer and interfinger with large tubes, and large irregular bodies extend into large tubes and pillowed lavas (Fig. 2.3, 2.4). Towards higher stratigraphic levels in the units, the following successions can be observed:

- pillows, conformably overlain by a large irregular body;
- large tubes / pillows / smaller pillows;
- large irregular bodies / large tubes.

Large irregular bodies continue into large tubes with pillowed rims and also branch into large tubes towards side and top. This

facies is overlain by pillow lavas. Pillow tops are resistant to weathering and stand out, whereas the central parts of pillow lavas are more weathered. Dike-sill transitions and sills are the intrusives in this unit. Some sills are phenocryst-rich, with accumulations of olivine, clinopyroxene and spinel phenocrysts in their center.

Several parallel faults (striking 350-10°/80-90°N) with a few meters offset occur in unit F. Some of these faults are associated with small amounts of breccias. The strike of the extrusives in this unit is about 90/20°N, the thickness is about 210 m.

This unit is separated from the overlying unit E by a fault with unknown offset. A fault breccia marks the fault zone.

2.3.9 UNIT E (Fig. 2.2f)

This unit consists dominantly of sheet flows (75%), large tubes and pillows (19%), extrusive breccia and hyaloclastites (1%), and sills (5%), all being aphyric. Sheet flows are the thick, ponded type, with a regular inner structure (Fig. 2.6). They are interlayered with pillow lavas and/or have these as lateral extension. At the base of the unit, sheet flows are the dominant lithologic type, but towards the top, sheet flows are interlayered with pillows and large tubes. Pillows are extremely vesicular. Sill-dike transitions crosscutting the sheet flows are found especially in the side canyon.

One major fault was observed between unit E and unit F (striking 0/65°N). One smaller fault in the side valley of the canyon (striking 240/80°N) has an offset of several meters. The attitude of the sheet flows is 90/20°N, the thickness of the unit is 140 m.

The upper boundary of this unit is marked by a transition zone (about 20 m thick) consisting of sheet flows interlayered with pillow lavas, overlain by pillow lavas of unit D. The boundary was drawn above the uppermost sheet flow of unit E.

2.3.10 UNIT D (Fig. 2.2f)

The unit consists of aphyric, and some slightly phyric lavas and large tubes (98%), a large irregular body (1%). and some sills (1%). Pillow lavas and large tubes are closely packed. The large tubes occur

at the base of the unit, they are 3 to 4 m in diameter. Towards the top of the unit, pillow lavas alone occur, and these decrease in size from 1.3 to 1.4 m to 0.8 to 1 m at the top. The large irregular body in the side valley is surrounded by pillows, but because of bad exposure the relationships to the adjacent rocks are not clear.

Within unit D, only a few small faults without visible offset were observed. The strike of the lavas is very constant with 90/20°N, the thickness of the unit is at least 120 m.

The boundary between pillow lavas of unit D and sheet flows of unit C is marked by a large fault with unknown offset.

2.3.11 UNIT C (Fig. 2.2g)

This unit is made up dominantly by sheet flows (80%). In addition, pillow lavas (11%), extrusive breccias and hyaloclastite (4%), and dikes and sills (5%) are present. Most of the sheet flows represent the regular, ponded type, up to 6 m thick, with a lateral extent of up to 150 m (Fig. 2.6). They are ponded against small fault scarps. Some sheet flows at the entrance of the Kamara Potamos are more irregular. Aphyric, vesicular pillows and extrusive breccia are interlayered with the sheet flows. A hyaloclastite-rich feeder dike feeds pillows of unit B (described in detail in section 2.2.4, Fig. 2.11). Parallel sills crosscut sheet flows and pillows, striking 330/30°N.

Several small faults (strike 340-0°/80-85°N) are present in unit C. They form a small graben system in which sheet flows are ponded. After the graben was formed (simultaneously with the formation of sheet flows), a feeder dike erupted lavas of unit B (Fig. 2.11, 2.15). The thickness of the unit is 70 m.

Aphyric sheet flows and pillow lavas of unit C are conformably overlain by phyrlic lavas and lava tubes of unit B (Fig. 2.15).

2.3.12 UNIT B (Fig. 2.2g)

This unit consists almost entirely of pillow lavas and large lava tubes (97%). Extrusive breccias and hyaloclastites make up 2 - 3% and dikes less than 1%. At the base of the unit, a dike cutting unit C

feeds the overlying phyric lavas of unit B (Kamara Potamos) (Fig. 2.15). Above that boundary, large tubes and pillows are interlayered. Further up in the stratigraphy, large tubes disappear, and pillow lavas of 1 to 1.5 m diameter dominate. In the top part of the unit, smaller pillows (about 1 m in diameter) are common, then they decrease in size to 0.5 to 1 m, and are overlain by extrusive breccias and miniature pillows of 10 to 20 cm in diameter. Pillows and large tubes are closely packed, and gradually decrease in diameter from the base to the top of the unit.

No faults occur in this unit. Faults of unit C do not extend into unit B in the Kamara Potamos. The strike of the extrusives is constant with 90/20°N; the thickness of the unit is 115 m.

The boundary to unit A was drawn where fresh, aphyric, large pillow lavas of unit A overlie oxidized, phyric, small pillow lavas and extrusive breccias of unit B.

2.3.13 UNIT A (Fig. 2.2h)

Pillow lavas and large lava tubes are the dominant lithology in this unit. Extrusive breccia and hyaloclastite constitute 7%, a large lava body 7%, and dikes about 1%. In the lower part of the unit, aphyric large pillow lavas and large tubes, and one large irregular body are exposed. The pillow size decreases, and large tubes disappear towards the central part of the unit. The central part of the unit consists of a layer of extrusive breccias and hyaloclastites ((Fig. 2.12), associated with a talus breccia (Fig. 2.13). For a detailed description of these breccias see sections 2.2.5 and 2.2.6. Higher in the stratigraphy, aphyric and phyric pillows are interlayered. In the phyric lavas, the phenocryst content increases from the base of the pillow to the closely packed zone in the center or in the lower half of the pillow. The top of the unit consists of phenocryst-rich pillows of 0.5 to 1 m in diameter.

A large irregular body is exposed in a small side valley to the west of the Akaki River. It overlies pillows of unit B and seems to be overlain by pillows of unit A. Fresh glass occurs in this large irregular body, probably formed by penetration of water into the cooling but still hot lava. From the base to the top of the unit,

large tubes and pillows decrease in diameter systematically. Two sills with phenocryst-rich centers crosscut the large irregular body at the base of unit A.

Only a few small faults with 1 to 3 m offset occur in the small side valley to the west. They offset the phenocryst-rich sills crosscutting the large irregular body. The extrusives strike 90/20-30°N, the thickness of this unit is 157 m.

The upper boundary of unit A (and the extrusive series) is marked by pelagic sedimentary rocks, limestones of Cretaceous age, which conformably overlie pillow lavas of unit A.

2.3.14 SUMMARY OF STRATIGRAPHIC UNITS

2.3.14.1 STRUCTURE

The attitude of the extrusive volcanics is almost constant with 90/20°N within units and between units. Locally, the dip may range up to 40° (unit K). Based on average dip of 20° and measured thickness of the stratigraphic units, the total thickness of the section is at least 1500 to 1700 m. Unit thicknesses vary between 70 and 370 m, averaging 125 ± 25 m (Table 2.3). In the Akaki River section only two major faults with unknown offset are present. They separate units C and D, E

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Table 2.3. Comparison of stratigraphic units

unit	thickness	sheet	pillows &	large	hyalo-	sills &
	m	flows	large tubes	bodies	clastite	dikes
		%	%	%	%	%
A	157	-	85	2	12	1
B	115	-	97	-	2	1
C	70	80	11	-	4	5
D	120	5	93	1	-	1
E	140	75	19	-	1	5
F	210	-	65	30	-	5
G	70	55	25	-	10	10
H	75	-	60	35	-	5
I	80	60	10	-	15	15
J	105	-	80	-	5	15
K	370	55	10	-	15	20
L	>200	-	60	-	20	20

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and F (Fig. 2.2.f) (strike around 0/65°N). It is possible that the total thickness of the sequence is over- or underestimated due to the unknown offset of these faults. Small faults occur throughout the section, with offsets of a few meters. Dikes in the lower part of the section strike about 0-30/80-90°, similar to the faults, and were emplaced nearly vertically into the extrusive rocks. Sills are oriented like extrusives, or may have variable orientations, especially dike-sill transtions. Weather-resistant altered zones with similar orientations as dikes and large faults are exposed in unit D.

2.3.14.2 ALTERATION

In the Akaki River section, two modes of sea floor alteration can be distinguished (Schmincke et al., 1983, Gillis & Robinson, 1985). The uppermost 100 to 150 m of the section (in unit A) consist of a red to reddish-green, highly oxidized and leached zone (see also breccia in Fig. 2.13), with an irregular lower boundary (Schmincke et al., 1983). Pillow margins are altered to smectite, minor zeolite and calcite. Olivine phenocrysts are completely replaced by carbonates, and Fe-oxides. Vesicles are filled with smectite, carbonate and zeolites (Gillis & Robinson, 1985). They have interpreted this type of alteration as prolonged sea floor weathering, which is superimposed on the other, less pervasive type of alteration of the remaining part of the section. The latter depends on lithologic type, cooling history, grain size and permeability (Gillis & Robinson, 1985). Secondary minerals in sheet flows are smectite, calcite, celadonite, clinoptilolite, mordenite, opal-C, opal-CT, chalcedony and quartz; whereas the pillow lavas are altered with smectite, calcite, analcime, phillipsite, nathrolite, gmelinite and chabazite.

There is no systematic increase in degree of alteration towards the base of the section, as was proposed by Smewing (1975). No consistent stratigraphic or metamorphic boundary can be drawn based on the secondary minerals (Gillis & Robinson, 1985). Within the units, the degree of alteration is often variable (units B, D, F, H, J). The lavas are fresher at the base of the unit and glassy rims are preserved, whereas at the top of the unit, the degree of alteration is higher, and less glass is preserved. This is probably due to the higher permeability of pillow lavas at the top of a unit, and maybe also due to the exposure to seawater for a slightly longer time.

However, the lack of sediments between the units suggests that the time between extrusion of two units was short. Furthermore, the altered zone at the top of a unit, as observed in unit B, only reaches down 1 to 2 m from the top of the unit.

2.3.14.3 UNIT BOUNDARIES

The contacts between stratigraphic units may be depositional (sharp or transitional) or tectonic (Table 2.4). Most depositional contacts between stratigraphic units are sharp, with small unconformities, caused by the topography of the older unit. However, the general dip of the extrusive volcanics in the units is the same. Pillow lavas may be overlain by sheet flows, or vice versa; or pillow intervals with differing characteristics overly each other (units H-G, B-A). The uppermost zone of the lower unit is often more altered than the base of the upper one (e.g. unit B-A). Transitional boundaries (Table 2.4) occur twice in the Akaki River section between K-J and E-D. In each case, sheet flows are the dominant lithologic type of the lower unit, the 20 to 50 m thick transition zone consist of sheet flows interlayered with pillows, and this is overlain by pillow lava and large tubes. Tectonic boundaries (between units F/E and units D/C) are formed by two large faults. In each case the lower (=older) unit consists of pillow lavas, and the upper (younger) unit consists of

Table 2.4. Unit boundaries		
1. depositional and sharp		
L - K	pillows	- sheet flows
J - I	pillows	- sheet flows
I - H	sheet flows	- pillows, large tubes
H - G	pillows	- pillows, large tubes, sheet flows
G - F	sheet flows	- pillows, large tubes
C - B	sheet flows, pillows	- pillows, large tubes, irregular bodies
B - A	pillows	- pillows, large tubes, irregular bodies
2. depositional and transitional		
K - J	sheet flows	- pillows, large tubes
E - D	sheet flows	- pillows, large tubes
3. tectonic		
F - E	pillows	- sheet flows
D - C	pillows	- sheet flows

sheet flows. In the case of the boundary F/E, the contact is not exposed but the sheet flows are of the thick, ponded type, so that ponding against the fault is suggested. This indicates that the fault is older than the sheet flows of unit E.

2.3.14.4 LITHOLOGY

In the lower parts of the Akaki River section the volcanics and the stratigraphic units show a more irregular structure than in the upper part. The change is from an irregular succession of extrusives to a more regular one, and this suggests that there was an evolution in the eruption style throughout time. Unit L consists of irregular pillow lavas (Fig. 2.9), large tubes and large amounts of extrusive breccias, the overlying unit K of an irregular succession of sheet flows (Fig. 2.14), extrusive breccias and a minor amount of pillow lavas. In the overlying stratigraphic units (J-A), sheet flows and pillow lavas are more regular and extrusive breccias are less abundant. These stratigraphic units consist of dominantly pillow lavas, large tubes, and large irregular bodies (units A, B, D, F, H, J) or contain mainly sheet flows and minor amounts of pillows (units C, E, G, I) (Table 2.3). Within these units, the lithologic types occur in certain stratigraphic successions, and common sequences are (Fig. 2.16):

1. Sheet flows, overlain by a transition zone of sheet flows, large tubes and pillow lavas, then overlain by pillow lavas and large tubes (units K-J, G-F, E-D).
2. Large irregular bodies (not present in all units), branching into large tubes, branching into and overlain by pillow lavas. In many units, these pillow lavas decrease in size towards the top of the unit (unit A, B, D, F, H, J) (Fig. 2.3, 2.4).

As no major breaks are observed within one of these sequences, it is suggested that these sequences formed in one volcano-tectonic event and represent single eruptions.

The intrusive style and abundance of dikes and sills evolves within the section. In the lower part the dikes are numerous and occur usually as multiple intrusions. The abundance of dikes gradually decreases, and upwards they occur more often as single intrusions. At this stratigraphic level, sills increase in number. Towards the top of

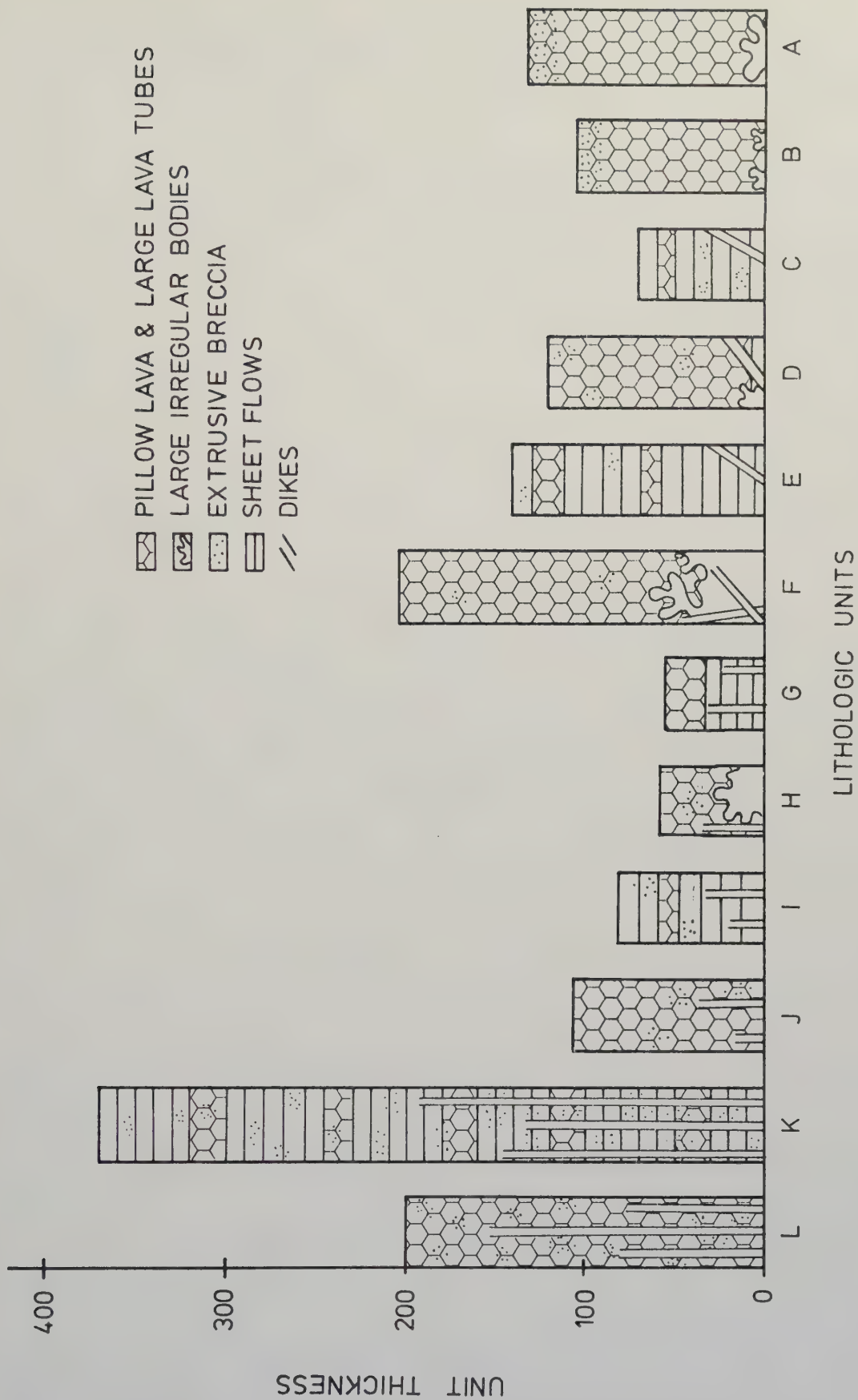


Fig. 2.16. Thickness and stratigraphic association of lithologic types in stratigraphic units A - L. Common successions are: sheet flows - pillows, large bodies - large tubes - pillows - extrusive breccia.

the section, only sills are present and their number decreases in the uppermost units.

2.4 COMPARISON WITH MODERN SUBMARINE VOLCANICS

Oceanic crust today is generated at divergent margins, i.e. spreading centers in major or back arc basins. The best studied areas are those at mid-ocean ridge spreading centers (Galapagos Rift in the Pacific and the Famous area in the Atlantic ocean), where direct observations were made from submersibles and deep tow cameras. Little information is available about the volcanology and constructional processes in back arc basins and in early stage island arcs. However, Hussong & Uyeda (1981) suggest that the crustal construction processes are the same at mid ocean ridges and in island arc regimes, e.g. in the Mariana arc.

The presence of the sheeted dike swarm in the Troodos ophiolite led to the interpretation that it formed in a tensional environment at a mid ocean spreading axis (Gass, 1968, Kidd & Cann, 1974, Kidd, 1977, Moores & Vine, 1971). However, Leitch (1984) argues that tensional regimes can also occur at convergent plate margins, i.e. island arc settings, or, in back arc basins. Thus, the presence of a sheeted dike swarm alone does not necessarily indicate a formation of the Troodos ophiolite at a spreading ridge in an ocean basin, but merely the formation in a tensional environment. The volcanologic construction processes should be very similar in tensional environments in any tectonic setting.

Thus, without making any assumptions about the tectonic setting of the Troodos ophiolite (except that Troodos has formed in a tensional environment), the volcanics will be compared to those of the Galapagos Rift and the FAMOUS area, simply because these areas are the best studied ones in the present-day oceanic crust.

2.4.1 LITHOLOGIC TYPES

The pillow lavas of the Akaki River section are very similar to those described from present ocean floor (Moore, 1975, Ballard & Moore, 1977), except that collapsed lava tubes or pillows were not found in the Troodos volcanics. Large tubes and the associated irregular bodies have not been described from recent oceanic ridges. This is probably

due to the fact that they cannot be observed from submersibles because they are always covered by a layer of normal sized pillows. In addition, their identification in drill cores is difficult. If the contact relationships are not clear, for example because of poor core recovery, larger irregular bodies might be mistaken for intrusive bodies. Thick holocrystalline flows with glassy margins overlain by pillow lavas were reported from site 449, in the Parece Vela Basin (Shipboard Scientific Party, 1981), these may be equivalents of the large irregular bodies described from the Akaki River section.

Sheet flows from present day ocean floor were first described by Lonsdale (1977) from the East Pacific rise. Ballard et al. (1979) observed different types of sheet flow surfaces at the Galapagos Rift. Smooth pahoehoe and wrinkled surfaces are more common than broken-up, hyaloclastite-rich surfaces. In Troodos, only sheet flows with a hyaloclastite-rich top were formed. The formation of these layers may be due to a high volatile content, indicated by the high vesicle content of the lava. Ballard et al. (1979) describe transitions from sheet flows into pillow lavas at the end of sheet flows, confirming that flow rate but not topography or chemical composition of the lava is the governing factor controlling sheet flow or pillow formation. This is consistent with the observations in the Akaki River section.

The amount of volcanoclastics is underestimated when looking at drill cores, because in those with poor core recovery (Robinson et al., 1980), the core material is biased towards massive flows. At high recovery rates (70% at the Bermuda Rise), volcanoclastics can make up to 20% of the core (Robinson et al., 1980). These authors distinguished two types of breccia, lithic (talus breccia) and glassy (extrusive) breccia. Heterolithologic breccias were also described from the La Palma Seamount (Staudigel & Schmincke, 1984) and have the same characteristics as the talus breccias occurring in the Troodos ophiolite. Hyaloclastite breccias of extrusive origin were also observed by submersible at seamounts at the East Pacific Rise, where hyaloclastite drapes down on volcano slopes (Lonsdale & Batiza, 1980).

2.4.2 STRUCTURE

Systematic successions of sheet flows, large lava tubes and large irregular bodies and overlying pillows were observed in the Akaki River section. Similar successions of sheet flows and pillow lavas were described from the Galapagos Rift (van Andel & Ballard, 1979, Ballard et al., 1982). The similarity of the sequences described also suggests a similarity in the inner structure of recent oceanic edifices. Volcanic events are episodic in recent oceanic crust (Ballard & van Andel, 1977, van Andel & Ballard, 1979), this is also consistent with the observations in the Akaki River section.

Van Andel & Ballard (1979) proposed a cyclic model for the construction of the sheet flow - pillow succession: rapid extension with high eruption rates of lava and sheet flow production is followed by pillow production at low effusion rates. Some time after the volcanic edifice is built up, a new axis of extension forms at the side of the volcano, and the whole volcano is transported laterally (Ballard & van Andel, 1977, van Andel & Ballard, 1979).

At slow spreading ridges, volcanos are between 100 and 250 m high (Ballard & van Andel, 1977). Lithologic units drilled in the Atlantic are generally less than 100 m thick. Volcanic edifices at the fast spreading East Pacific Rise are larger, up to 300 m high (Francheteau & Ballard, 1983). Troodos stratigraphic units are between 100 and 200 m thick, and if several units are combined into a volcano, e.g. units D and E, the succession may be up to ca. 300 m thick. Thus the dimensions of Troodos volcanic edifices are similar to the range of those found on the ocean floor.

2.5 THE CONSTRUCTIONAL MODEL

2.5.1 A COMPLETE VOLCANO CROSS SECTION

When the information from all units is combined, a complete volcano cross section can be constructed. From the base to the top of a volcano, the following facies types are found (Fig. 2.16, 2.17):

1. Basal sheet flows. These are associated with minor amounts of pillow lavas, and occur in units C, E, G and K.
1. Large irregular bodies. They branch into large tubes and pillows towards the sides and top and are exposed best in units F and H.

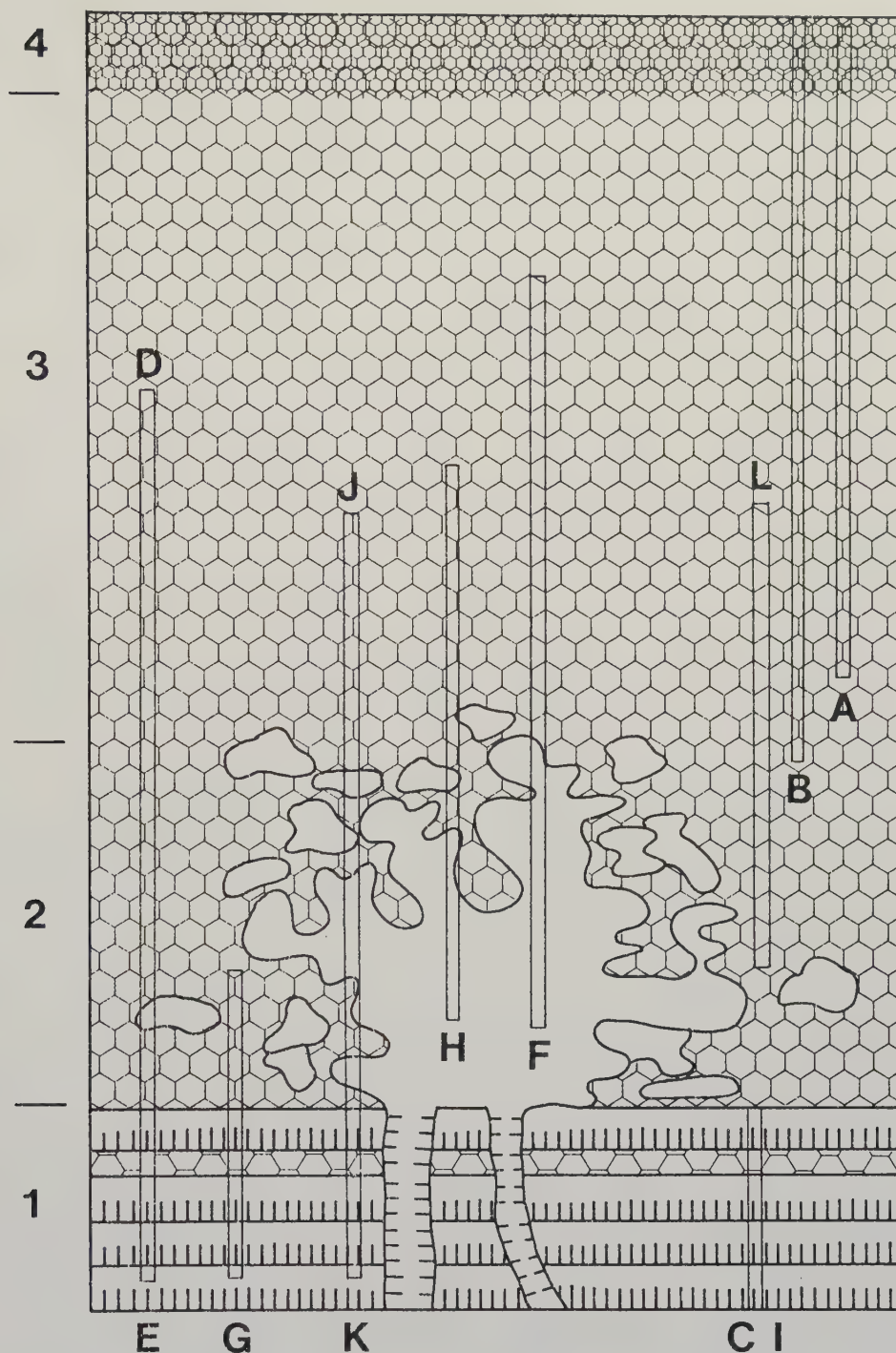


Fig. 2.17. Schematic cross section through a volcano. Facies types are indicated: 1. sheet flows  associated with minor amounts of pillows; 2. large tubes and large irregular bodies ; 3. normal-sized pillows ; 4. minipillows and extrusive breccia . The stratigraphic succession of units A - L is indicated by vertical bars.

3. Large tubes. They branch and interfinger with pillow lavas and are common on the lower parts of units A, B, D, F, G, H, J, and L.
4. Normal-sized pillow lavas. They decrease in size towards the top of the succession; sometimes layers of tubes occur in this zone. Normal pillow lavas make up most of units A, B, D, F, H, and J.
5. Miniature pillows and extrusive breccias with hyaloclastite. They are best exposed in units A and B.

Several of these cycles, not always complete, overlie each other in the Akaki River section. Considering the succession of lithologies in the separate units, it appears that several units with transitional boundaries could be combined to one major succession cycle, e.g. the units K-J, E-D, and C-B. These volcanos are elongated, probably up to 800 m wide (unit F). In outcrop they may be up to 800 m long (unit B). Because they are probably symmetrical and only part of the volcano is exposed, it is suggested that they may be up to 1600 m long.

2.5.2 EVOLUTION OF A PILLOW VOLCANO THROUGH TIME

The construction of a volcano and its shape depend on the shape of the feeder system, the topography on which lava is erupted, and the duration and intensity of eruption. A cyclic constructional mode for submarine volcanos in the Akaki River section can be inferred from the structural relationships between and within stratigraphic units. The evolution and construction of such a volcano proceeds through several stages without major interruption, followed by a period without volcanism, but with possible tectonic activity. Several of these cycles follow each other through the evolution of the Akaki River section.

2.5.2.1 STAGE 1 - THE SHEET FLOW STAGE

To construct a volcano, a feeder system is necessary. This consists probably of several fissures, coming up to the sea floor in a small area. Dikes start to produce lavas through these open fissures. In the beginning, the eruption rate may be low in some cases so that the lava level in the fissure-dike varies, leading to formation of extrusive breccias and hyaloclastites in the upper part of the dike. A hyaloclastite-rich feeder dike of this type is exposed in unit C, feeding pillow lavas of the overlying unit B (Fig. 2.11, 2.15).

In general, sheet flows make up the basal part of a typical volcano (Fig. 2.17), but do not occur in the upper part of the volcano, which is composed of pillow lavas, large tubes and large irregular bodies. In general, factors controlling the formation of sheet flows instead of pillows are: the flow rate, the volume erupted, the cooling rate and the previous topography. The previous topography results either in ponded or unponded sheet flows, but seems not to prevent sheet flow production in general. This suggests that the flow rate and the volume erupted at the early stage of construction of a volcano must be relatively high, too large to produce pillow lavas. In units C and E, the volume erupted was large for each single sheet flow, and the flow rate was probably high and rather constant for a certain period of time to form regular ponded flows, or as in unit I, to form unponded flows, but with only minor pillow lavas associated. In contrast, the irregular associations of sheet flows and pillows in unit K suggests the flowrate was variable, forming sheet flows, pillows and extrusive breccias in a irregular succession. Unit L lithologies with regular pillow lavas and extrusive breccias suggest a similarly variable, but lower flow rate, because the volume erupted was never large enough to allow the formation of sheet flows.

In the first stage of volcano construction, sheet flows are produced and fill in the given topography (Fig. 2.18). The sheet flows are either ponded or unponded. At the end of this stage of volcano construction the flow rate and the erupted volume decrease. The sheet flows or pillows are formed intermittantly and a sheet flow-pillow zone is formed. This type of transition is exposed between units E and D. Eventually sheet flow production ceases and only pillows are produced.

Sheet flows do not occur in all units. This may have several reasons; they may occur only locally, because they are filling in a given topography and may not be exposed in a section such as the Akaki River section, where not each stratigraphic unit represents a complete stratigraphic section through the volcano. The other possibility is that sheet flows were never deposited in the first place. This could be due to the eruption style; flow rate and erupted volume may not have been large enough for the formation of sheet flows, but only for the formation of pillow lavas.

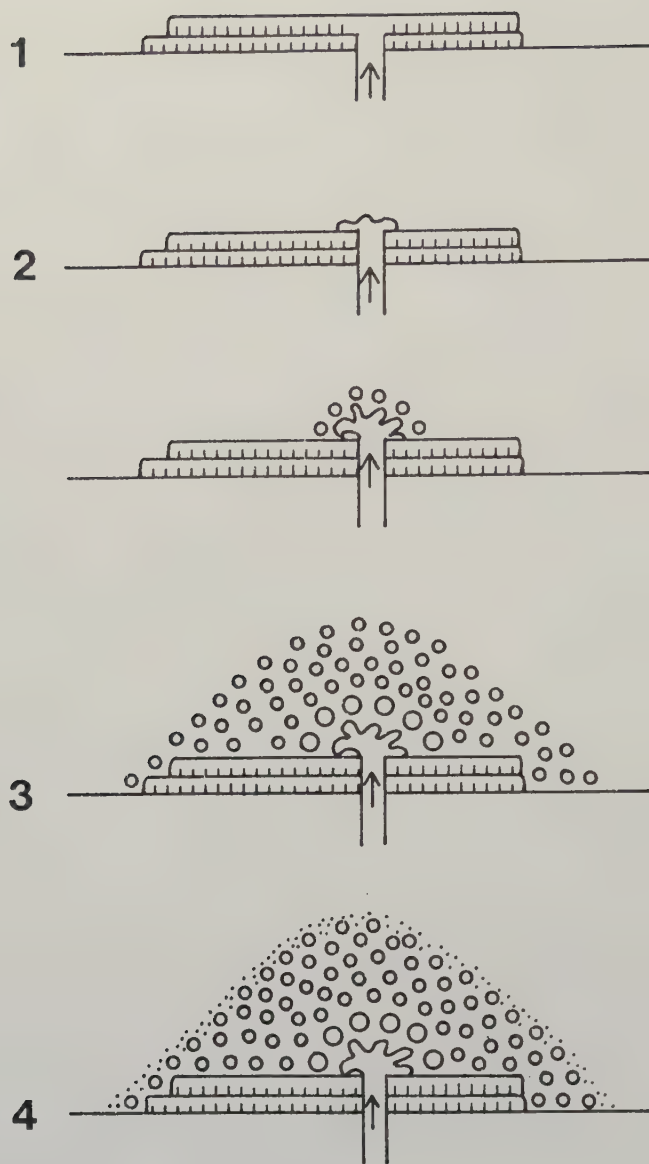


Fig. 2.18. Schematic diagram of evolutionary stages of a volcano. Sheet flows , large bodies , large tubes and pillows , minipillows and extrusive breccias . Stage 1: sheet flow stage, stage 2: formation of the feeding system, stage 3: formation of normal-sized pillows, stage 4: end of the eruption, formation of minipillows and extrusive breccias.

2.5.2.2 STAGE 2 - THE FORMATION OF THE FEEDER SYSTEM

At the beginning of the second stage of volcano construction, the flow rate and the volume erupted are low, and then increase slowly. At the beginning, pillow lavas are produced. This probably leads to the restriction of the open fissures to a circular or elongated vent. These pillow lavas are thought to build up a small pile. With an increasing flow rate and erupting volume, some of the pillows expand in diameter to allow for a higher flow rate (Fig. 2.5, 2.18). These are the first large tubes that form. They grow side by side, with pillow lavas between them. Thus, they always have lateral support and can grow vertically and horizontally in an irregular fashion. Typical examples for these tubes are exposed in unit F (Fig. 2.4).

When the flow rate increases, some of the large tubes and some of the pillows continuously expand to larger diameters. Some of the large tubes may join in the central part of the volcano and form the first irregular bodies, and former normal sized pillows, now large tubes, branch off from there (Fig. 2.3). This situation is best exposed in unit F (Fig. 2.2e). The bulk of the normal sized pillows remain constant in size and cool down, indicating they are already too cold to be expanded easily. Meanwhile, the continuous production of pillowed lavas towards the side and top of the volcano continues. By expansion of the large tubes to large irregular bodies and normal sized pillows to large tubes the feeder system for the pillowed part of the large tubes has been established.

From the outside and top of the volcano, only normal-sized pillows, miniature pillows, and extrusive breccias are visible throughout this entire development, because the large tubes and the feeding are always covered with smaller pillows.

2.5.2.3 STAGE 3 - FORMATION OF THE MAIN PILLOWED PART

With a constant eruption rate, the part of the volcano consisting of normal sized pillow lava will be built up in a short period of time (Fig. 2.18). If a new larger pulse of lava erupts, some of the normal sized pillows expand to form large tubes higher up in the stratigraphy of the volcano. This is exposed in unit H (Fig. 2.2.d). As soon as the flow rate decreases or stabilizes, normal pillows will be produced again, but the newly formed large tubes will stay. Pillows decrease in

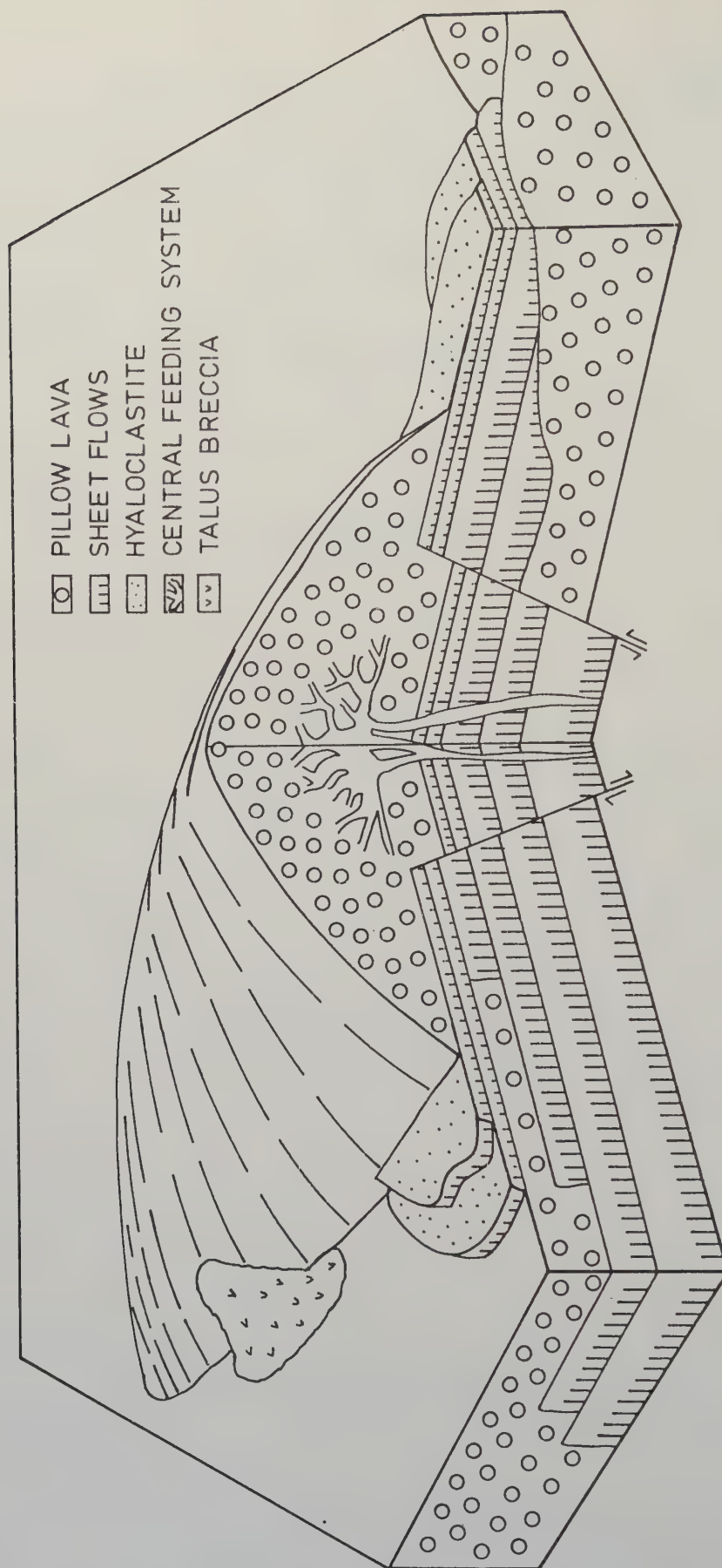


Fig. 2.19. Schematic block diagram of a volcano. The volcano height is about 100 to 300 m, its width up to 800 m, the total length up to 1600 m.

size with increasing distance from the vent areas, because the erupted volume is distributed into many pillow branches.

2.5.2.4 STAGE 4 - END OF THE ERUPTION CYCLE

A slow decrease in flow rate leads to a decrease in pillow size. Miniature pillows and extrusive breccias with hyaloclastite are produced. This marks the end of a volcanic episode. After eruption has ceased, the feeder system of the volcano cools to the fine to medium grained large tubes and large irregular bodies exposed in the Akaki River section. A brief period without volcanic activity follows before the next volcanic cycle starts with new dikes erupting sheet flows. A block diagram of such a volcano is given in Fig. 2.19.

The magma reservoir must be large enough to produce a stratigraphic unit, because units are deposited within a volcanic event without a break. Time gaps between the construction of single volcanos cannot be long, because there is no sediment in between units, and oxidation of the top of the unit is not very pervasive, only a slight change in freshness is observed.

2.5.3 FORMATION OF THE AKAKI RIVER SECTION

Stratigraphic units in the Akaki River section also represent a time sequence, from L as the oldest to A as the youngest volcanic edifice in the section. In the early stages of construction of the sequence, lavas of units L and K show an irregular succession of pillowed flows, extrusive breccias and sheet flows. The upper units J through A were constructed by eruption cycles, in which a more regular succession of sheet flows, pillow lavas with large tubes and large irregular bodies is overlain by normal sized pillow lavas.

The succession from irregular to regular volcanic sequences suggests that the eruption style changed throughout time, depending on flow rate, volume erupted and the duration of the eruption. High flow rates and large volumes erupted lead to sheet flow formation (Fig. 2.20, 2.21); lower flow rates, and smaller volumes result in formation of pillow lavas. At constant flow rates, regular sheet flows and pillow successions are formed. In contrast, irregular, variable flow rates cause production of variable pillow sizes, extrusive breccias, or sheet flow - pillow - extrusive breccia associations.

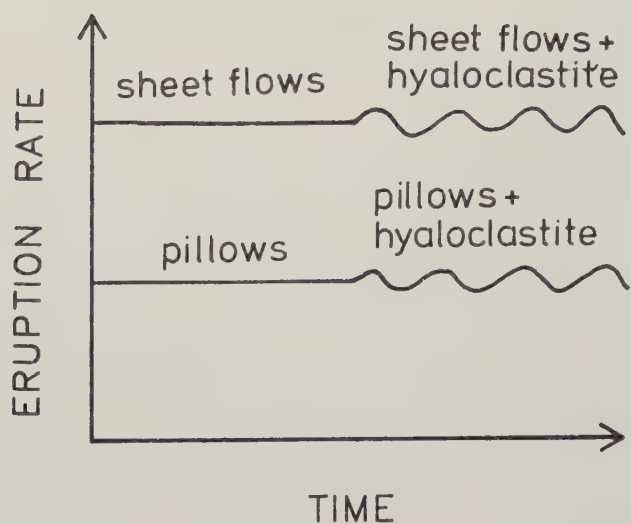


Fig. 2.20. Estimated relative eruption rate versus time for typical lithologic types. Constant high eruption rate: formation of sheet flows; variable high eruption rate: formation of sheet flows and hyaloclastites; constant low to medium eruption rates: formation of pillow lavas; variable low to medium eruption rates: formation of pillow lavas and hyaloclastites.

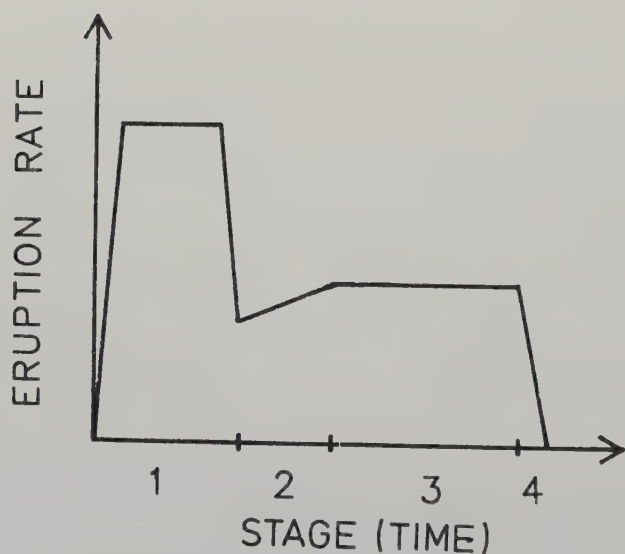


Fig. 2.21. Estimated relative eruption rate versus time in the evolution of a typical volcano. 1. formation of sheet flows, 2. formation of the feeding system, 3. formation of normal sized pillows, 4. end of the eruption with formation of minipillows and extrusive breccias.

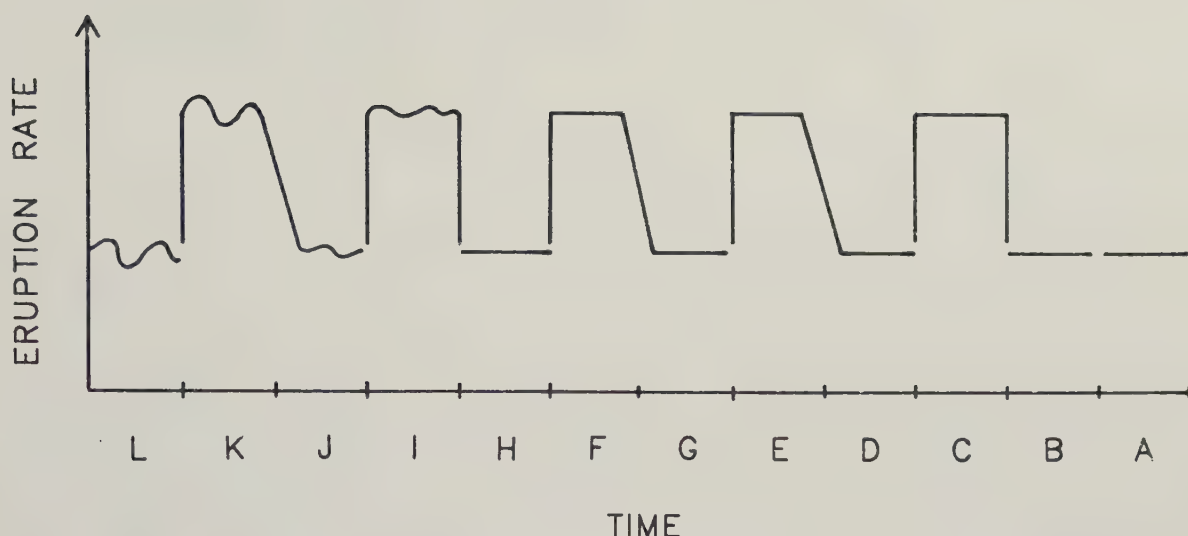


Fig. 2.22. Estimated relative eruption rate versus time for the evolution of the Akaki River volcanics. Pillow lavas and extrusive breccias of unit L: variable, medium flow rates. Sheet flows of unit K: variable, but medium to high flow rates. Then follows a cyclic succession: rather constant low to medium flow rates erupted pillow lavas, and also rather constant, but higher flow rates erupted sheet flows of the overlying units J through A.

The following conditions are proposed for the formation of the Akaki River section and are shown in Fig. 2.22. Medium flow rates with very variable intensities, with small to medium erupted volumes formed the irregular pillow lavas and extrusive breccias in unit L (Fig. 2.22). Variable, but medium to higher flow rates with larger erupted volumes caused the formation of irregular sheet flows, extrusive breccias and pillow lavas of unit K. Then follows a cyclic succession of rather constant low to medium flow rates with medium volumes of lavas erupted to form pillow lavas, and also rather constant, but higher flow rates and volumes of lava erupted to produce sheet flows of the overlying units J through A. It is possible that at late stages (unit A), sheet flows were not produced at all. This would indicate a decrease in volcanic production towards the end of the volcanic history of the sequence. It is possible, however, that sheet flows did form at that time, but are not exposed in the Akaki River section.

Intrusives, such as dikes and sills clearly form after the

formation and cooling of the lithologic unit they crosscut, but no further conclusions about the relative time of their emplacement are possible.

2.6 CONCLUSIONS

Field data from the Akaki River section set constraints about the volcanic processes operating at the sea floor for the Troodos ophiolite and may have implications for recent submarine volcanics. Several extrusive lithologic types, pillow lavas, sheet flows, large tubes, large irregular bodies, several types of breccias, and intrusive types such as dikes and sills were distinguished. Hyaloclastite breccias form by spalling-off of glassy margins, or by granulation of lava at low effusion rates. Coarser grained larger irregular bodies form simultaneously with pillow lavas and large tubes, continue laterally into these, and have pillowed margins. The subdivision of the Akaki River section into twelve stratigraphic units was based on the occurrence and characteristics of extrusive lithologic types. These units comprise areas or stratigraphic intervals of volcanics with similar characteristics, e.g. dominantly sheet flows or dominantly pillows. One or several of these stratigraphic units represent a cross section through a volcano. These volcanos have elongated shapes, are about 100 to 300 m high, up to 800 m wide, and probably up to than 1600 m long.

A cyclic constructional model for the evolution of the Troodos submarine volcanos could be developed. It comprises the following stages: (1) the sheet flow stage (high eruption rate); (2) the formation of the feeder system, consisting of large irregular bodies, large tubes, and pillowed lavas (starting at low, then continuously increasing eruption rates); (3) the formation of the main pillowed part (at a rather constant eruption rate); (4) the end of the eruption cycle, formation of miniature pillows and extrusive breccias (at low eruption rates).

Volcanic events are episodic, because units have well defined upper and lower boundaries. Each unit was erupted in a single volcano-tectonic event, because there are no major depositional breaks within units (e.g. sediments, or oxidation surfaces). Time gaps between volcanic events were short, because no sediments are found between

units. and oxidation zones are restricted to a few meters at the top of a given stratigraphic unit.

The eruption style changes throughout the evolution of the Akaki River section. First lavas were erupted with medium and high flow rates, but the intensity of the eruptions was very variable. This led to the formation of irregular pillows and sheet flows associated with large amounts of extrusive breccia. Then follows a transition into more regular cycles, with large flow rates and volumes of lava producing sheet flows and medium flow rates and volumes of lava producing pillows. Less volcanic breccia is associated with these volcanics.

Lithologic types from the Troodos ophiolite show the same characteristics as those from recent oceanic volcanics. The typical succession of sheet flows, large bodies, large tubes, and pillow lavas are described both from the Troodos ophiolite and from modern oceanic crust. Volcanic construction is episodic in both cases. It is suggested that the mode of construction proposed for the volcanic edifices of the Troodos ophiolite may also be applicable for volcanos at oceanic ridges today.

CHAPTER 3. PETROGRAPHY AND MINERAL CHEMISTRY OF THE AKAKI RIVER VOLCANICS

In this chapter, the petrography and mineral chemistry of the volcanics from the Akaki River section are presented (Table A.3). Locations and brief sample descriptions are given in Fig. 2.2 and Table A.1 (Appendix). Petrographic descriptions are given in Table A.2 (Appendix).

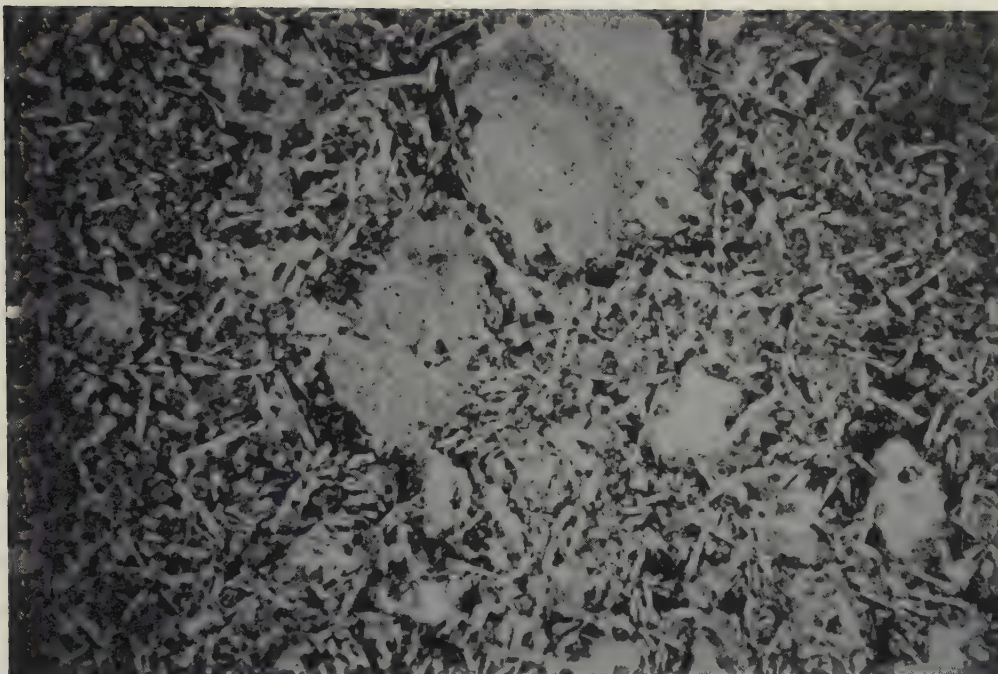
3.1 TEXTURE

Most Akaki River volcanics are aphyric or sparsely microphyric with single phenocrysts and/or glomerophenocrysts (Fig. 3.1). The following phenocryst-parageneses are present in order of decreasing abundance:

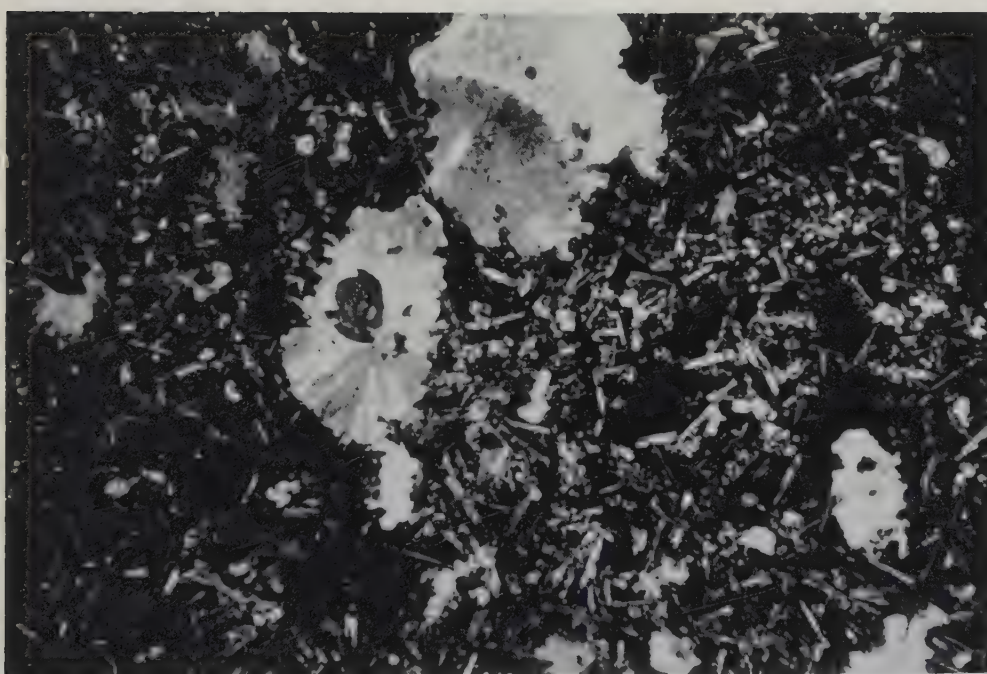
- clinopyroxene - plagioclase
- clinopyroxene
- olivine - clinopyroxene
- olivine
- olivine - clinopyroxene - plagioclase
- plagioclase

In general, the extrusives in the lower part of the section are aphyric to sparsely plagioclase-phyric, whereas the extrusives in the upper part of the section are aphyric to sparsely clinopyroxene-olivine phyric. A few samples are moderately to strongly phyric, these rocks have large olivine crystals as main phenocryst phase and occur as extrusives only in unit A at the top of the section and occasionally as intrusives throughout the entire section.

All transitions between glassy and fine grained textures are present in the groundmass. The former occur on pillow-, sheet flow-, and dike rims and as hyaloclastites, and the latter in pillow-, sheet flow-, and dike interiors inside from the quenched margin. The fine grained groundmass of e.g. pillow lava interiors consists of intergrowths of skeletal clinopyroxene and plagioclase, with subordinate amounts of opaques and a very fine grained mesostasis (Fig. 3.1). In general plagioclase laths show no orientation, but in some cases the laths may be subparallel, e.g. in dikes. The fresh glass of e.g. pillow rims and hyaloclastite is pale to dark brown and contains a



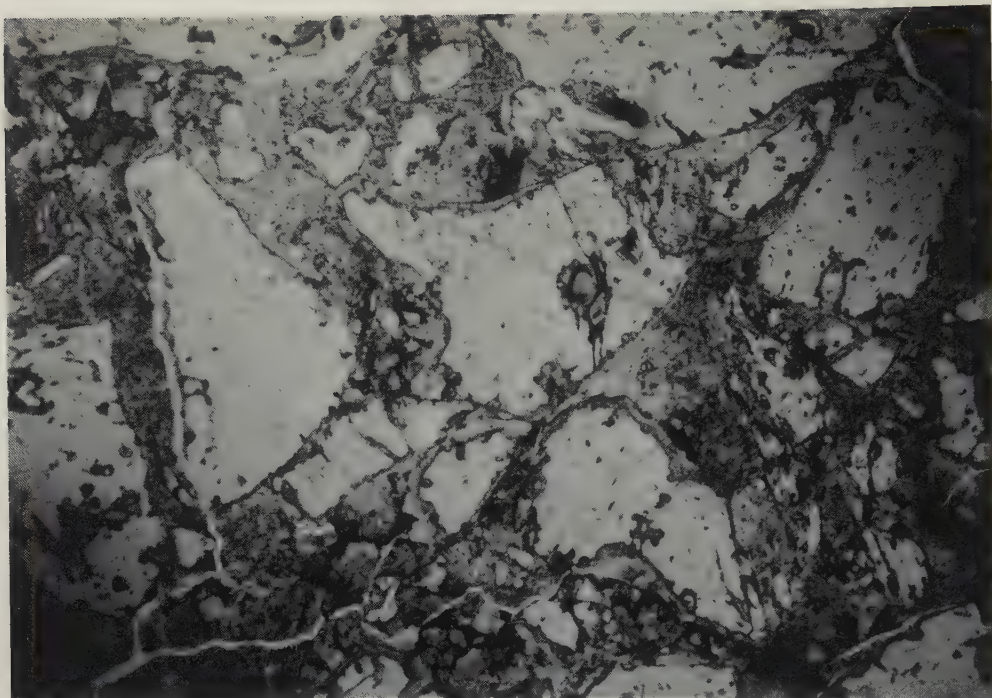
a)



b)

Fig. 3.1. Crystalline pillow lava. a: polarized light, b: crossed Nicholls. Groundmass consists of clinopyroxene, plagioclase and altered glass. Vesicles are filled with carbonates. Width of photograph is about 1 cm.

a)



b)



Fig. 3.2. Hyaloclastite . a: polarized light, b: crossed Nicholls. Pale brown glassy fragments are up to 5 mm in diameter and contain minute microphenocryst of clinopyroxene. Note freshness of fragment centers and yellow brown palagonite alteration on their rims.

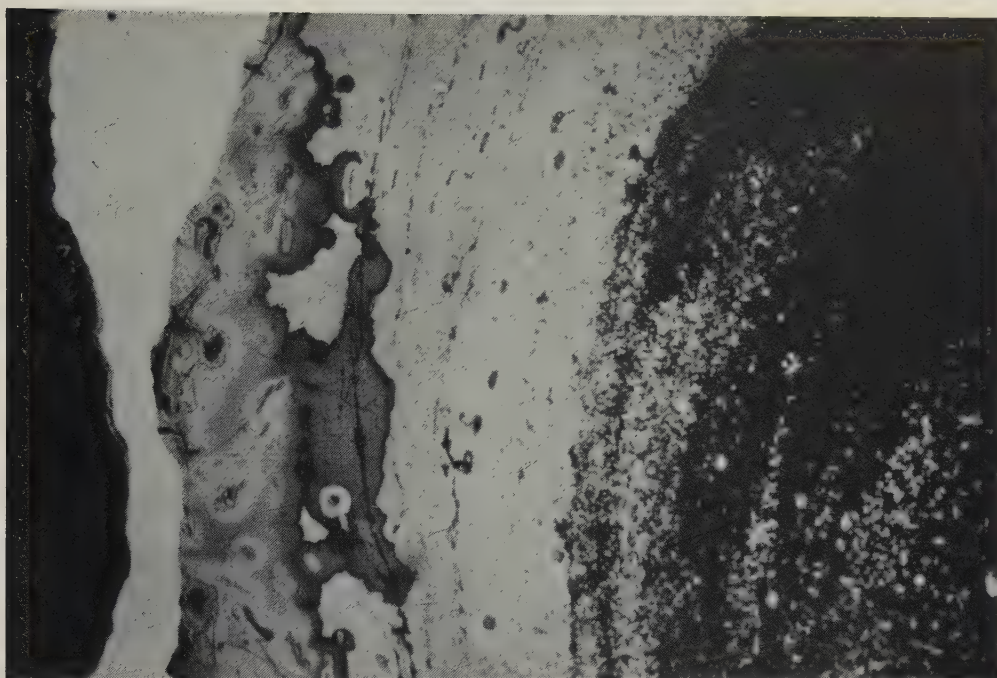


Fig. 3.3. Glassy rim of a dike. From left to right: altered glassy margin with yellow brown palagonite; pale brown fresh glass with microlites of cpx; crystalline groundmass with clinopyroxene and plagioclase. Width of photograph is about 1.5 cm.

few microlites of clinopyroxene and plagioclase (Fig. 3.2, 3.3). Hyaloclastite consists of 2 to 5 mm large angular glass shards in a matrix of very fine grained glass shards (Fig. 3.2).

Vesicles (1 to 5%) are common in pillow lavas and sheet flows whereas dikes and sills are less vesicular.

3.2 PHENOCRYSTS

Olivine phenocrysts are euhedral to subhedral and range in size from 0.2 to 10 mm. They contain dark brown spinel euhedra (0.3 mm) as inclusions. Olivine occurs as single crystals or as glomerophenocrysts, sometimes associated with subordinate amounts of clinopyroxene phenocrysts. Most olivine crystals are completely replaced by clay minerals and carbonates. Olivine phenocryst compositions (Table A.3) range from Fo₈₆ to Fo₈₃ (Fig. 3.4).

Clinopyroxene phenocrysts are pale brown in thin section, euhedral to subhedral, and range in size from 0.3 to 1 mm. Optical zoning

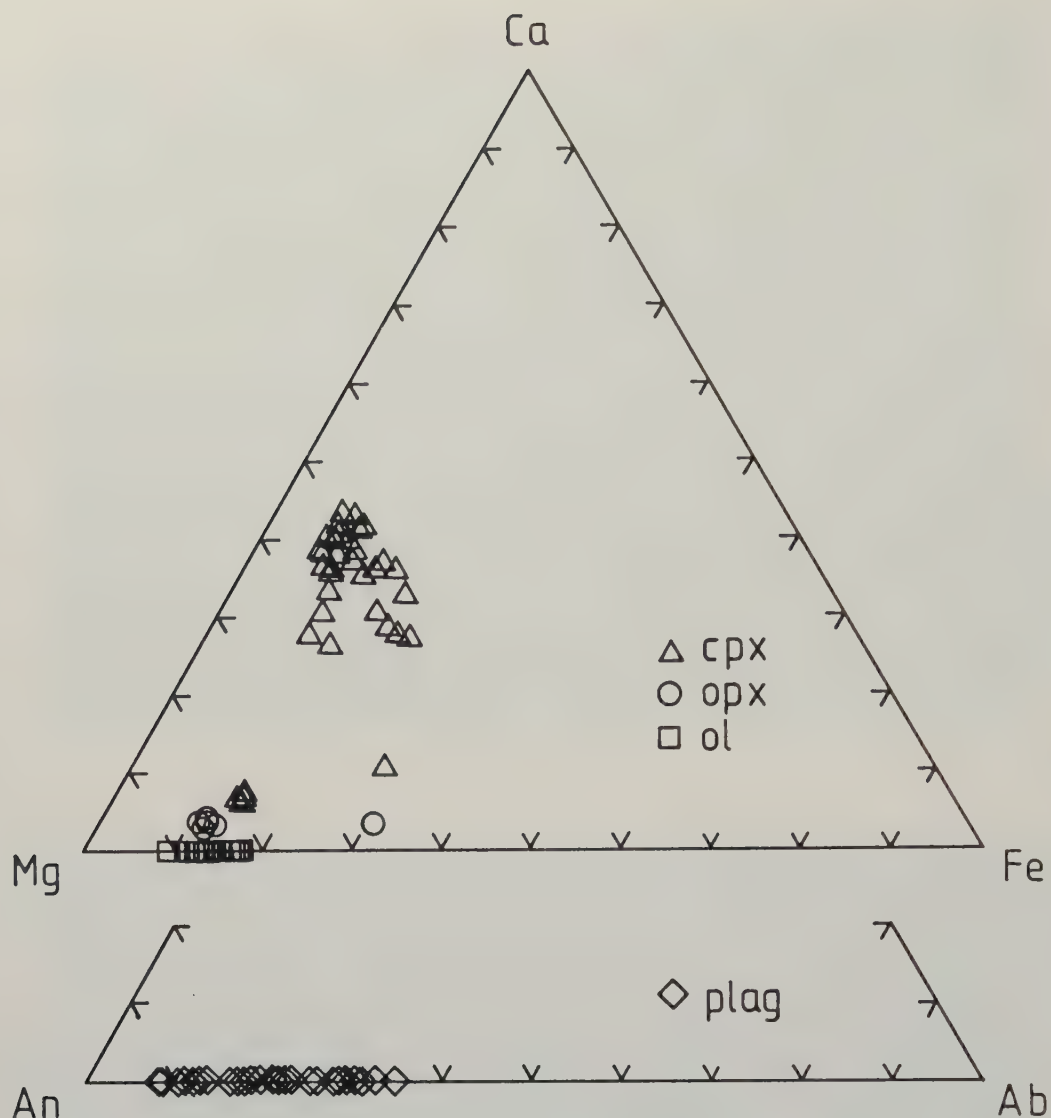


Fig. 3.4. Mineral chemistry of Akaki River volcanics.

occurs in some cases. Clinopyroxenes occur as single crystals, or as glomerophenocrysts intergrown with plagioclase. The crystals are usually fresh, but in some cases their rims are altered to clay minerals. The chemical compositions of clinopyroxene phenocrysts (Table A.3) range from endiopside to augite (Mg# 79 to 89) (Fig. 3.4), and some Mg-pigeonites are present. Subcalcic augites occur as quench crystals or as rims on phenocrysts (Mg# 62).

Plagioclase phenocrysts are mostly equant or lath-shaped euhedral to subhedral crystals, and range in size from 0.3 to 0.9 mm. Some crystals are zoned and albite twinning is common. Plagioclase occurs

mostly in glomerophenocrysts, either consisting of plagioclase only or intergrown with clinopyroxene; single crystals are rare. Plagioclase phenocrysts are mostly fresh, but some are partly replaced by clay minerals. Plagioclase ranges in composition (Table A.3) from An₉₀ to An₇₀ (Fig. 3.4).

One orthopyroxene microphenocryst was observed (hypersthene, Mg# 68) in the Akaki volcanics. In sample LIM from the Limni area several mafic orthopyroxene phenocrysts were analyzed (Table A.3).

3.3 ALTERATION

Most crystalline rocks are moderately to strongly altered. Secondary phases replacing groundmass and phenocryst phases are chlorite, smectite, carbonates, zeolites, quartz and celadonite. Glass is commonly altered to palagonite and clay minerals, but fresh glass is present in many rocks. Most vesicles and cracks are lined or filled with clay minerals, zeolites, and carbonates (Fig. 3.1). These observations are consistent with those from drill cores from ICRGD drill-holes CY-2 and CY-2a (Sunkel et al., submitted).

CHAPTER 4. ANALYTICAL TECHNIQUES AND CHEMICAL COMPOSITION OF AKAKI RIVER VOLCANICS

4.1 SAMPLING AND SAMPLE PREPARATION

The rocks of the extrusive series of the Troodos ophiolite are altered, but fresh volcanic glass occurs as 0.5 to 1 cm thick rims on pillows, sheet flows and dikes, and as fragments in hyaloclastite breccias. Large samples (up to 20 kg) of pillow lava, dike, sheet flow or hyaloclastite breccia were collected throughout the Akaki River section. A suite of samples representative of the entire section, including glass and whole rock samples from intrusive and extrusive rocks were selected for analysis. In addition, two glass samples from other localities in the Troodos extrusive series (Kalavassos and Limni, Fig. 1.2) were taken. A brief description of the location and petrography of the samples is given in Fig. 2.2 and in Tables A.1 and A.2.

Whole rock samples were crushed to pieces of about 2 cm diameter using a small hydraulic splitter. The fragments were washed in distilled water, and the least altered pieces without vesicles or veins were selected. These fragments were crushed to lentil-size with a steel mortar, then sieved to remove possible metal particles, and crushed to powder in an agate mill.

Considerable time and effort was expended to prepare separates of volcanic glass that were free of contamination introduced by secondary alteration or laboratory procedures. To obtain separates of acceptable quality, the glass fragments had to be clean, transparent and free of any alteration, vesicles, veins, altered or unaltered phenocrysts. These fragments were obtained by crushing, washing with reagent grade ethanol and hand picking under a binocular microscope. Acid rinsing was rejected, because this would leach the glass and remove mobile trace elements, particularly the alkali elements. The procedure used to prepare the glass separates was as follows: Glass-whole rock fragments were crushed first with a hammer and then in a steel mortar to 2 to 3 mm size. During this procedure, the sample was sieved often to avoid the production of too much fine grained material that could not be used for handpicking. This fraction was sieved and cleaned ultrasonically in distilled water for 20 to 30 minutes to remove

surface dust, then rinsed with reagent grade ethanol and dried. The resulting fragments were handpicked to obtain a glass rich fraction. This fraction was again hand crushed in an agate mortar to 0.3 to 1 mm size to obtain clean glass shards. Again the fractions were sieved, washed in reagent grade ethanol in an ultrasonic bath, rinsed and dried. The fractions of 400 to 600 μ m were then handpicked under a binocular microscope to obtain glass separates free of altered phenocrysts, vesicles or any surface alteration. Finally, the separates consisting of clean shards were checked for inclusions under ethanol. Minute, fresh quench microphenocrysts were considered to have formed directly by the melts during the last stage of eruption and fragments containing such microphenocrysts were not removed. The final separates were 99.9% pure unaltered glass as checked under the microscope.

Altered glasses and whole rocks corresponding to the glass samples represented by clean separates were also separated by handpicking during the preparation of the glass separates.

4.2 ANALYTICAL TECHNIQUES

4.2.1 MICROPROBE

Major element compositions of small glass samples and phenocrysts were determined in polished thin sections by wavelength dispersive microprobe analysis, in part at the Electron Optical Centre, University of Adelaide by B. Griffin, and in part at Memorial University of Newfoundland. Glass compositions were determined using a defocussed electron beam, in order to avoid vaporization of the glass. A mineral standard was measured and is given in Table A.3. In some cases, the Na₂O concentrations are too low, due to vaporization of the glass by the electron beam. For example, sample 415 gave 1.05 % Na₂O by microprobe analysis but 2.51 % Na₂O when analyzed by AA. Na₂O values determined by microprobe will not be used in the following discussion.

4.2.2 XRF

Major and trace elements (Rb, Sr, Ba, Zr, Y, V, Cr, Co, Ni) of part of the whole rock samples were determined on fused glass pellets (Li-meta/tetraborate was used as flux) using a Philips PW1400 X-ray fluorescence spectrometer at Ruhr Universität Bochum by H. Niephaus.

Several standards were measured and are given in Table A.4. At Memorial University, Rb, Sr, Nb, Zr, and Y were determined by G.A. Jenner on pressed powder pellets for the remainder of the whole rocks and Nb, Zr, and Y on the glass separates. Standards are given in Table A.5.

For 11 samples, Zr was determined using both the XRF at the Ruhr Universität Bochum and at Memorial University, with different results (Fig. 4.1, Table A.6). The values obtained at the Ruhr Universität Bochum are systematically higher (Fig. 4.1). However, both methods give reproducible Zr data. To obtain a consistent data set for Zr, the Zr data obtained using the XRF at Bochum are adapted to the ones determined at Memorial University using the linear equation:

(recalculated Zr) = $11.12 + 0.955 * (\text{Zr measured using Bochum XRF})$,
that was obtained from the regression through the data points in Fig. 4.1. Recalculated values are marked + in data tables.

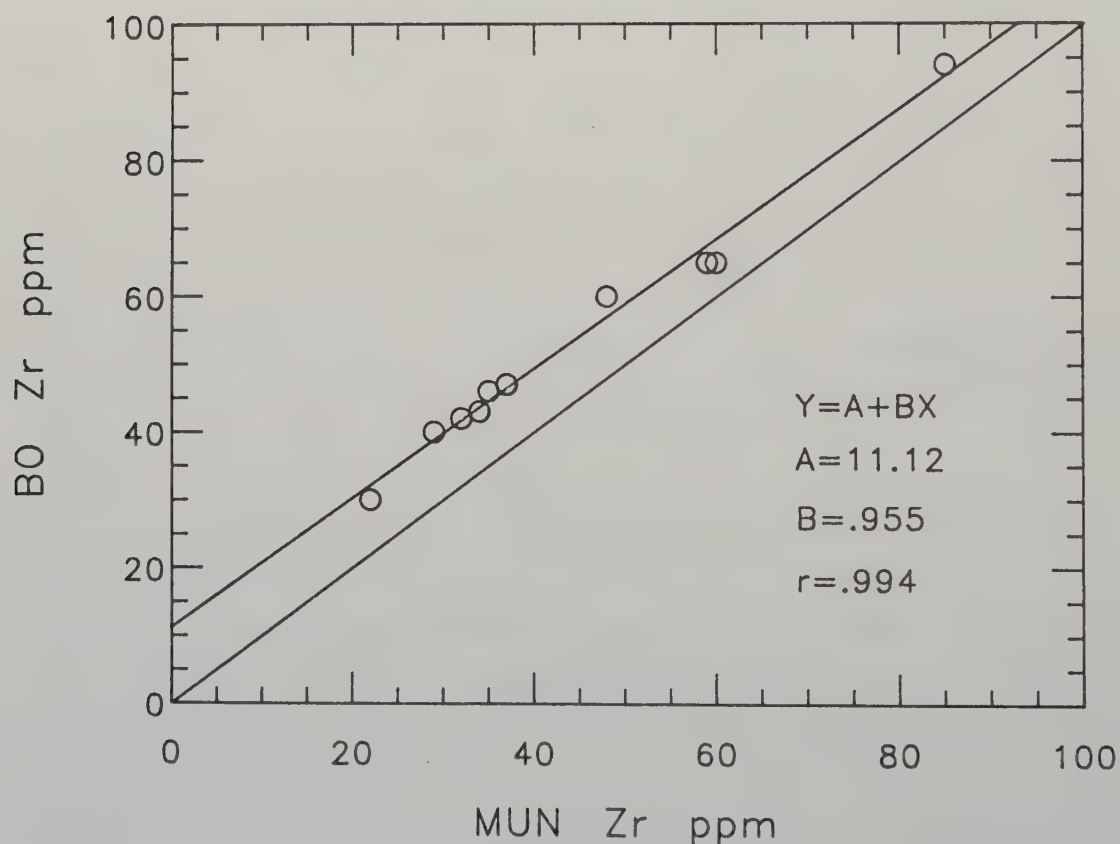


Fig 4.1. Zr concentrations determined at Ruhr Universität Bochum versus Zr concentrations determined at Memorial University. Slope and intercept of the regression are given.

4.2.3 ATOMIC ABSORPTION

The major elements of glass separates (excluding Na and K for the glass separates), the remainder of the whole rocks, and Ni were analyzed using atomic absorption at Memorial University by G. Andrews. The method is adapted from Langmyhr & Paus (1968), Abbey (1968), and Buckley & Cranston (1968). Standards are given in Table A.7.

4.2.4 Fe-II

At Memorial University, ferrous and ferric iron of whole rocks and glass separates were determined by titration modified after Wilson (1955) by G. Andrews. At Ruhr-Universität Bochum, Fe-II was determined on whole rocks by H. Niephaus using semi-automatic potentiometric titration of the samples digested in hydrofluoric acid - silver perchlorate, with standard potassium bromide solution.

4.2.5 VOLATILES

Volatiles were determined as loss on ignition at 1000°C at Memorial University by G. Andrews on whole rocks and glass separates. At Ruhr Universität Bochum H₂O and CO₂ of whole rocks were determined separately by H. Niephaus. CO₂ was determined by closed system coulombmetric titration of a Ba-perchlorate solution into which were passed the gases produced by passing oxygen over the sample roasted in a tube furnace. H₂O was measured by closed system coulombmetric titration of a non-aqueous Karl Fischer reagent into which was passed the carrier gas (N₂) containing water stripped from the sample by heating in a Pt-crucible to 1300°C in an induction furnace. M. Garcia determined the volatile composition of one glass separate, by degassing it in a vacuum by heating it to 1250°C at the rate of 5.5°C/min. The released volatiles were monitored as a function of time and temperature using a mass spectrometer.

4.2.6 INSTRUMENTAL NEUTRON ACTIVATION

Na, Sc, Cr, Hf, Ta, and Th on glass separates were determined by instrumental neutron activation at the University of Leuven, Belgium by J. Hertogen. The errors are Sc and Co ± 1 ppm, Hf ± 0.06 ppm, and Na $\pm 0.04\%$. The abundances of Th and Ta are near the limit of detection, even though long counts and a high flux irradiation were used. The errors for these elements are ± 0.007 ppm for Ta and ± 0.04 ppm for Th.

4.2.7 ISOTOPE DILUTION AND ISOTOPIC COMPOSITION

K, Rb, Cs, Sr, Ba, and REE abundances of glass separates, altered glasses and selected whole rocks were determined by isotope dilution analysis. The methods used have been described by White & Patchett (1984). Duplicate analyses of Sm, Nd, Rb, and Sr were made on some samples using Sm-Nd and Rb-Sr mixed spikes, in place of the otherwise used mixed alkali and REE spikes (Table A.8). Sr and Nd isotopic compositions were measured in the same manner as reported by White & Patchett (1984). Sr isotopic compositions were determined on leached (1 hour in hot 6N HCl) and unleached portions of the same sample. Blank levels were determined for all elements and are negligible in all cases (Table A.9). Trace element concentrations and isotopic compositions of the USGS international standards BCR, BHVO, AGV, JB, and GSP were determined as well and are also given in Table A.9. The single determination error for La, Gd, and Lu is 3%, for the remainder of the REE it is 2%, for the alkalis and alkaline earths about 5%. The Nd and Sr composition of these standards as well as those of the "La Jolla" standard for Nd (obtained from G. Lugmair), the "Eimer & Amend" for Sr, and NBS 982 for Pb are given in Table A.10. Chemical separation of the Pb was done using the method described by Manhès et al. (1978) and White & Dupré (1986). Pb isotopic composition was measured by a static multicollector method described by Todt et al. (1983). All isotope dilution and isotope composition measurements (except for oxygen) were performed on Finnigan MAT 261 mass spectrometers at Max-Planck-Institut für Chemie, Mainz.

Oxygen isotopes of glass separates, altered glass, and selected whole rocks were analyzed at the University of Western Ontario by R. Kerrich. Oxygen was extracted from the glasses using bromide pentafluoride, followed by quantitative conversion to CO₂ prior to mass spectrometric analysis (Clayton & Mayeda, 1963). Isotopic data are reported as $\delta^{18}\text{O}$ values in per mill relative to SMOW. Analysis of NBS 28 gave 9.8‰ (Coplen et al., 1983). The average overall reproducibility of $\delta^{18}\text{O}$ values is 0.18 ‰ (2 sigma).

4.3 RESULTS

Mineral compositions (determined by microprobe) are given in Table A.11.1 - A.11.4. Chemical compositions of whole rock (determined by XRF and AA) and glass samples (major elements determined by microprobe)

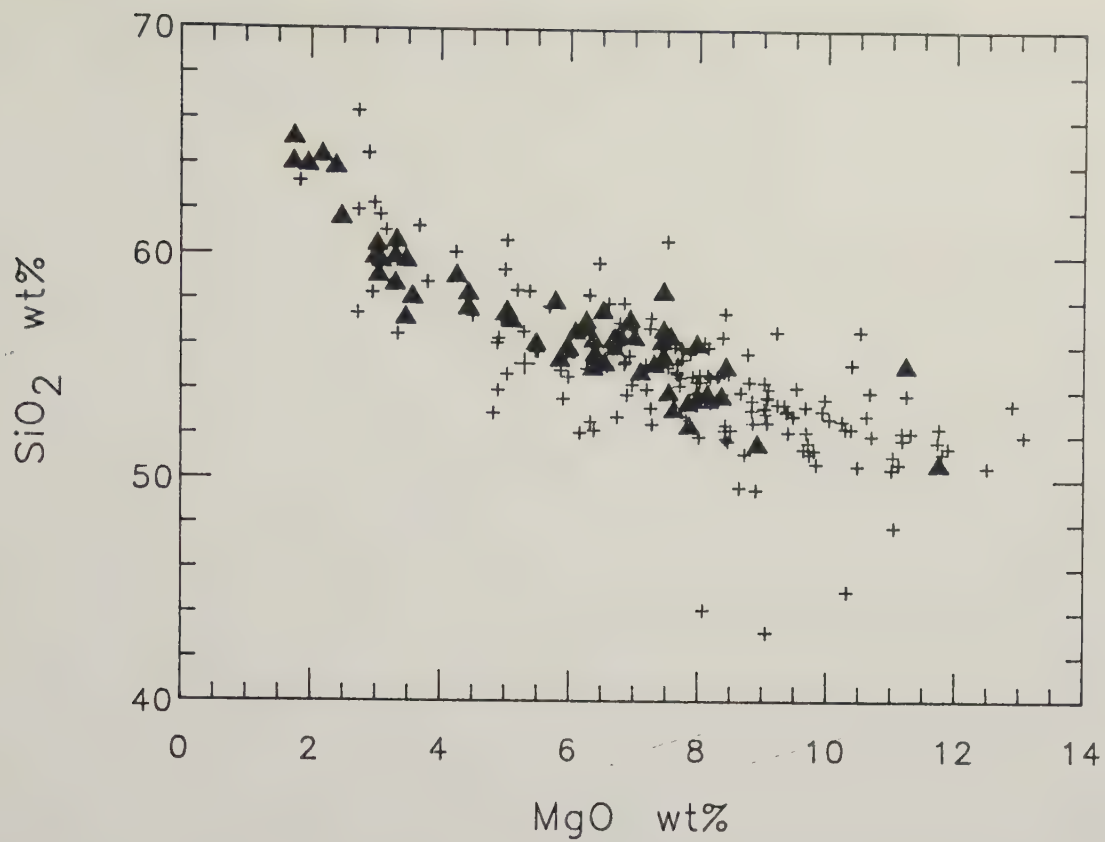


Fig. 4.2. MgO versus SiO_2 for glasses (triangles) and whole rocks (crosses).

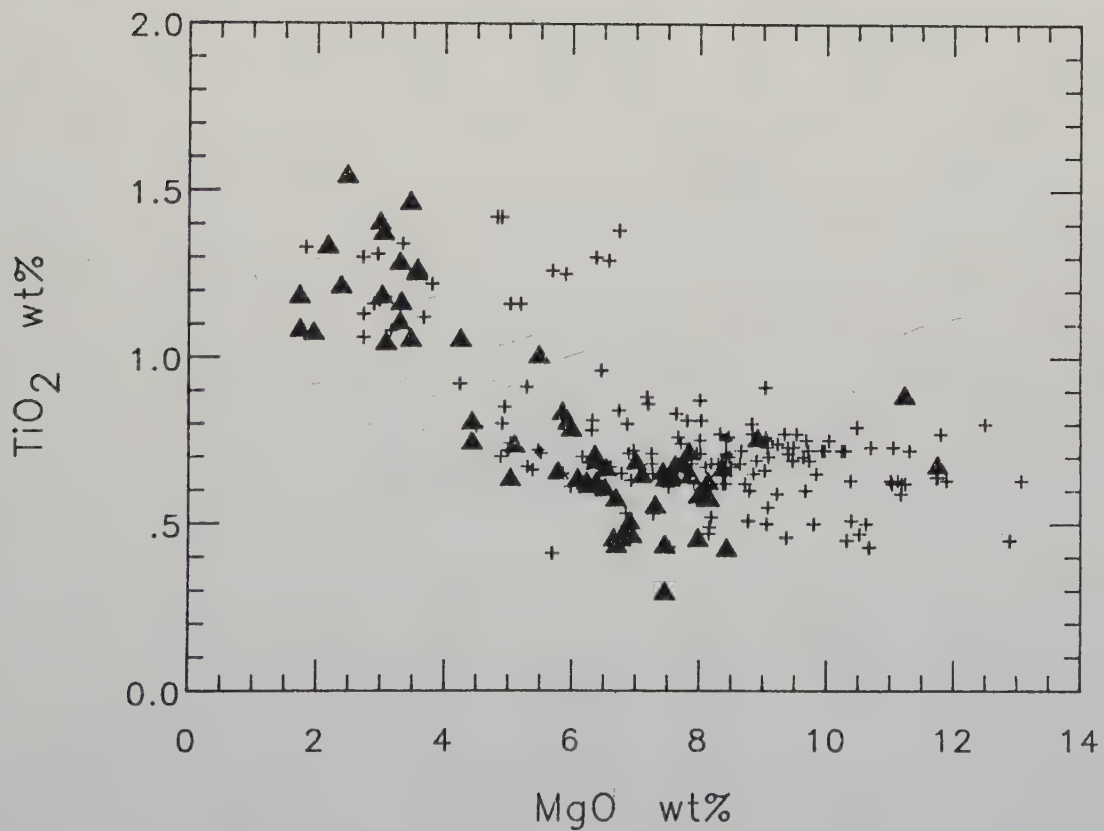


Fig. 4.3. MgO versus TiO_2 for glasses (triangles) and whole rocks (crosses).

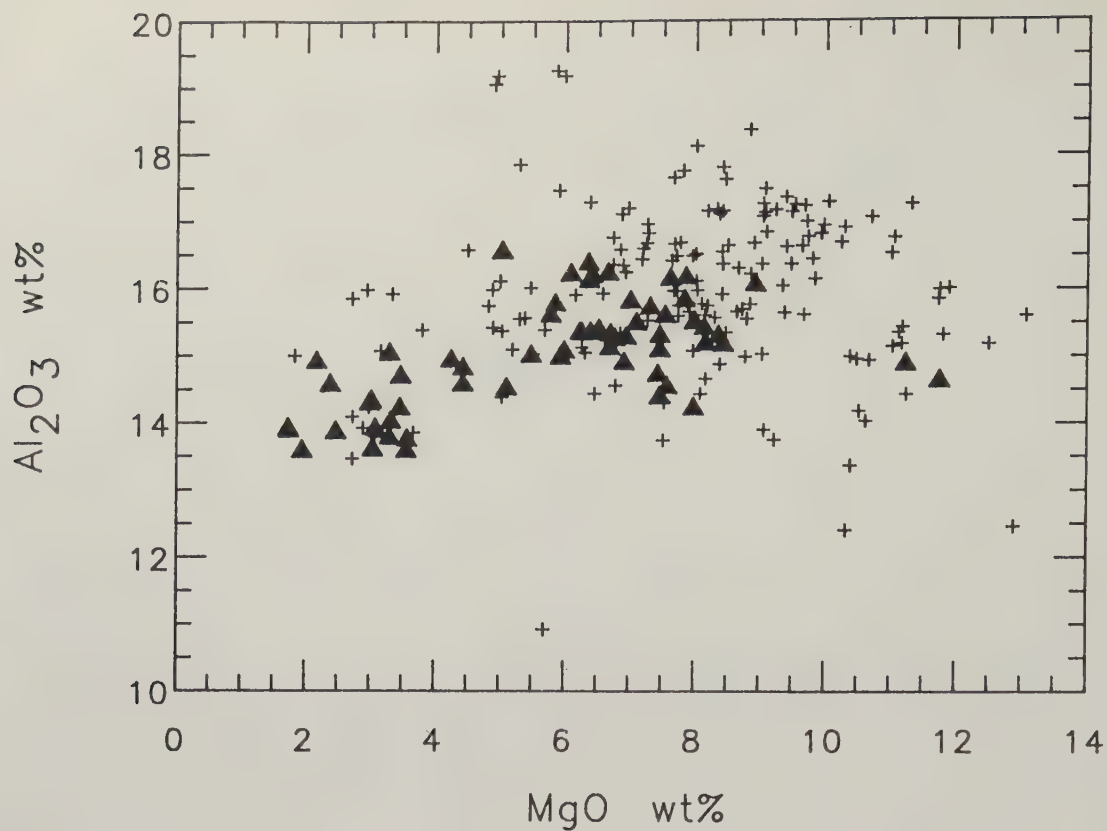


Fig. 4.4. MgO versus Al_2O_3 for glasses (triangles) and whole rocks (crosses).

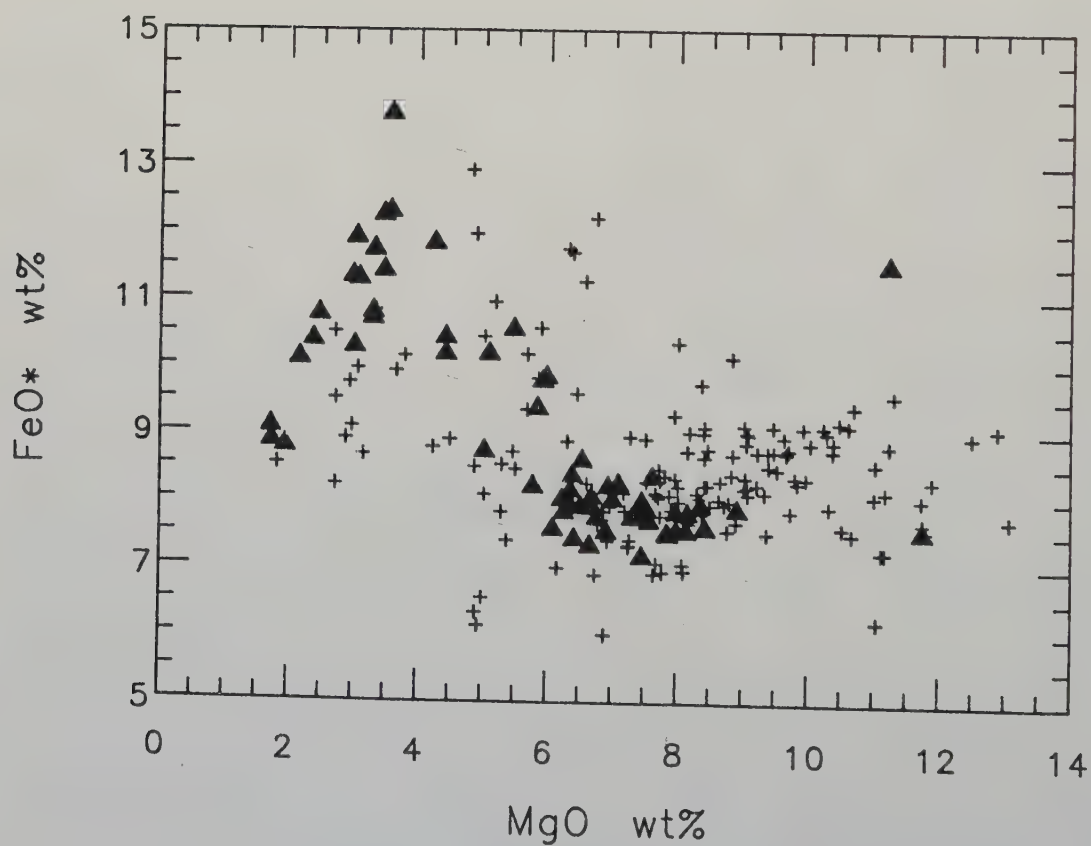


Fig. 4.5. MgO versus FeO^* for glasses (triangles) and whole rocks (crosses).

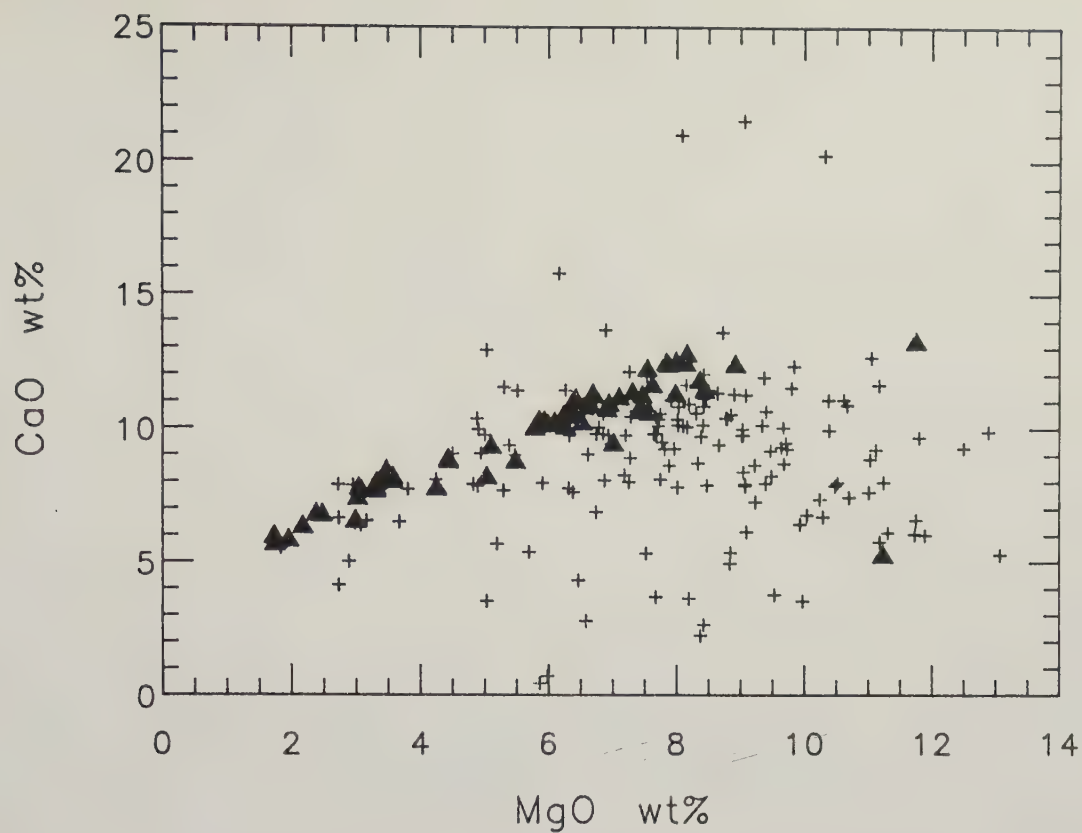


Fig. 4.6. MgO versus CaO for glasses (triangles) and whole rocks (crosses).

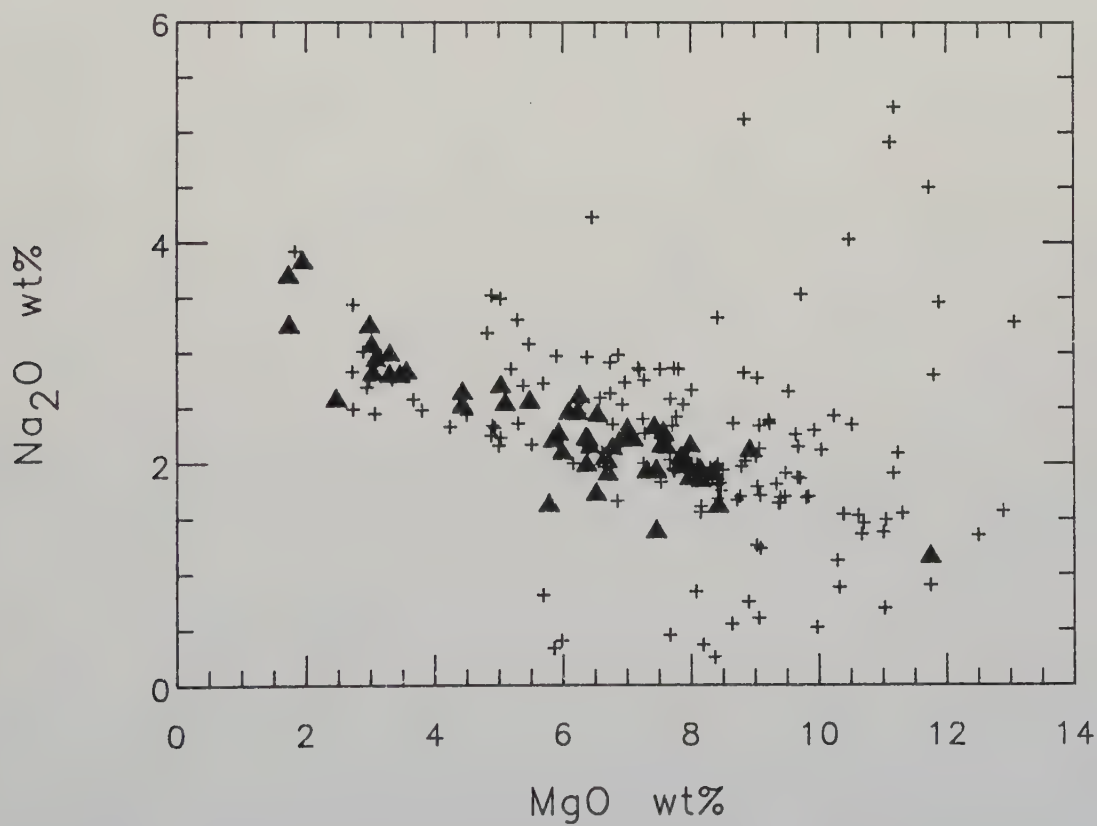


Fig. 4.7. MgO versus Na₂O for glasses (triangles) and whole rocks (crosses).

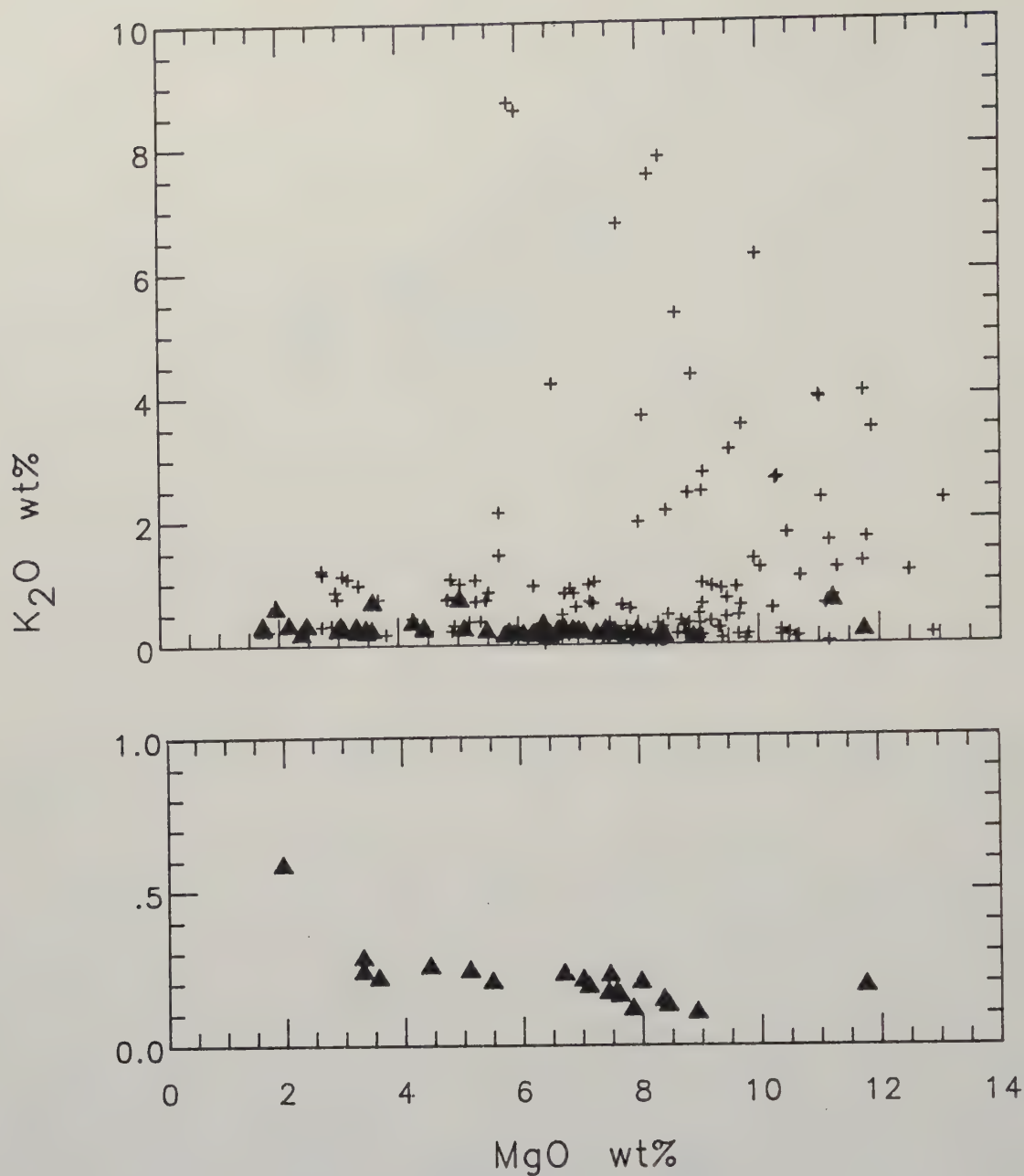


Fig. 4.8. MgO versus K₂O for glasses (triangles) and whole rocks (crosses). The lower part of the diagram shows only glass separates analyzed by isotope dilution.

are given in Table A.12. Compositions of glass separates, altered glasses, and selected whole rocks are given in Tables A.13 - A.18.

4.3.1 MAJOR ELEMENTS

The major element data are shown as functions of MgO in Fig. 4.2 - 4.8. The recalculated, volatile-free compositions of the glasses range from basalt (less than 52% SiO₂), basaltic andesite (52 to 56 % SiO₂) through andesite (56 to 62 % SiO₂) to dacite (62 to 66 % SiO₂) using the classification of Gill (1981). Whole rock compositions show a larger spread in SiO₂ contents (34 to 66 %). MgO-concentrations in whole rocks ranges from 2 to 27 %. Samples with more than 14 wt% MgO are olivine phenocryst-rich pillow or dike interiors and are not shown in the variation diagrams (Fig. 4.2 - 4.8). With decreasing MgO, there is an increase in FeO* (total Fe as FeO), SiO₂, TiO₂, Na₂O, and K₂O. At the same time, a decrease in CaO and Al₂O₃ is evident when only glass samples are considered. Whole rock samples show the same correlations, but less pronounced, and the data display a larger scatter. This is most obvious for K₂O, Na₂O, and CaO, and less for CaO and Al₂O₃ (Fig. 4.2 - 4.8). Volatile contents of the glass separates range from 2 to 5%. All glasses are quartz-normative (Table A.19).

On an AFM-diagram (Fig. 4.9) the glasses show a Fe-enrichment trend and lie within the tholeiitic field of Gill (1981). Whole rocks show a larger scatter and also plot into the calcalkaline field, as a result of their high Na₂O and K₂O contents.

In the Total Alkali Silica (TAS) system, a classification for igneous rocks (Le Bas et al., 1986), using the water-free calculated concentrations of SiO₂ and Na₂O + K₂O, the glasses and whole rock compositions fall in several fields (Fig. 4.10). Glass compositions are dominantly classified as basaltic andesites, and andesites, the exception being two basaltic and one dacite sample. Most whole rocks follow these systematics, but a significant number are located in fields with higher Na₂O + K₂O contents. This trend of the whole rocks is also evident in Figures. 4.7 and 4.8.

4.3.2 TRACE ELEMENTS

The incompatible trace elements were divided into several groups according to their ionic character. High field strength (HFS) elements were defined as having an ionic radius/charge ratio of less than 0.2 (Saunders et al., 1980). These are Zr, Hf, Ti, Nb, and Ta. Low field strength (LFS) elements were defined as having an ionic radius/charge

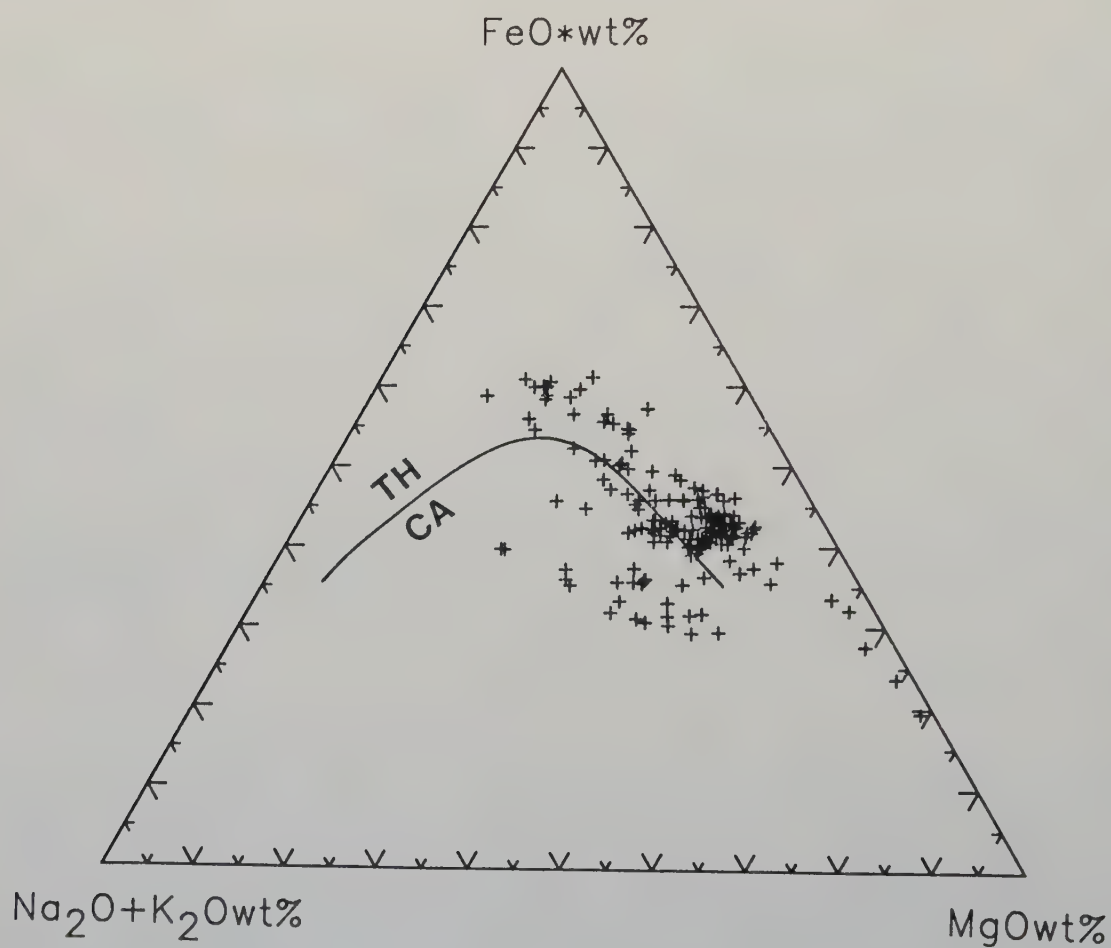
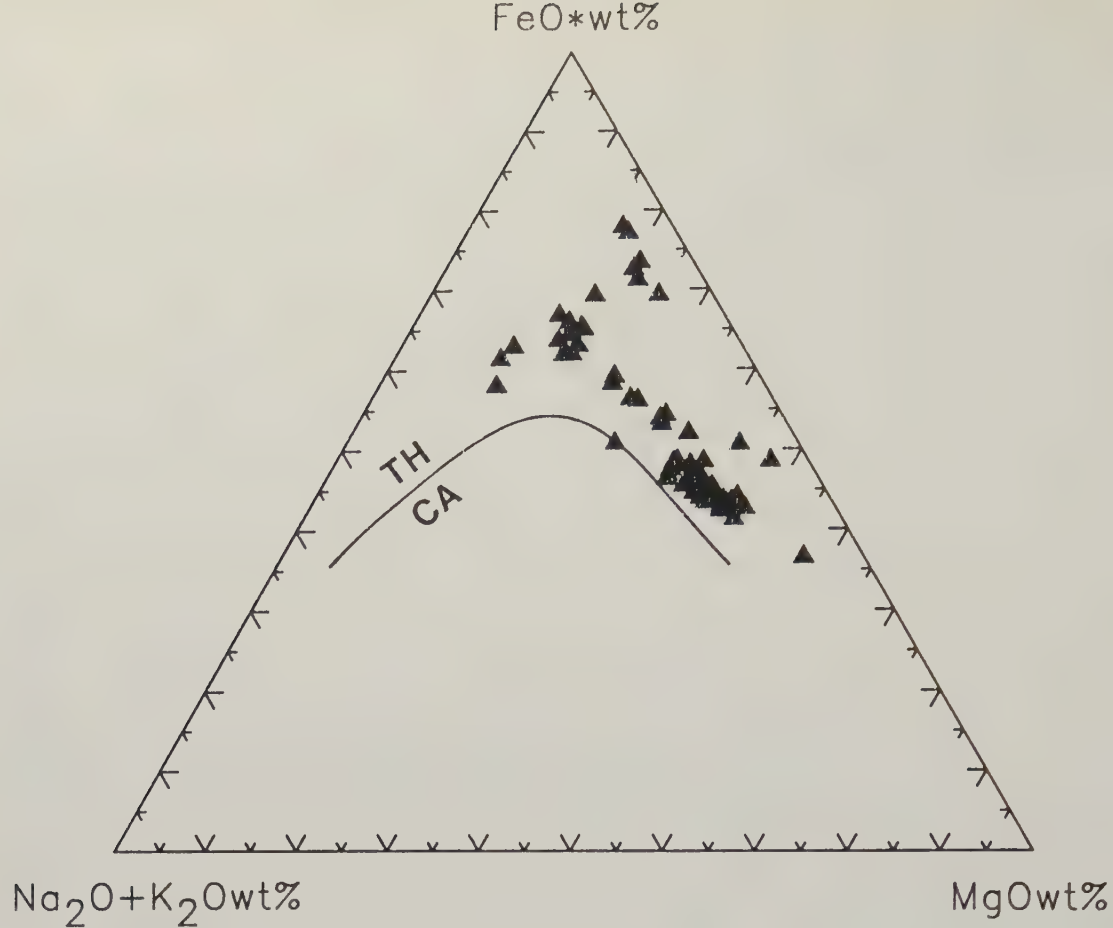


Fig. 4.9. AFM diagram for glasses (triangles) and whole rocks (crosses). All glass compositions fall in the tholeiitic (TH) field, whereas whole rock compositions (with higher Na_2O and K_2O) also fall in the calcalkaline field (CA).

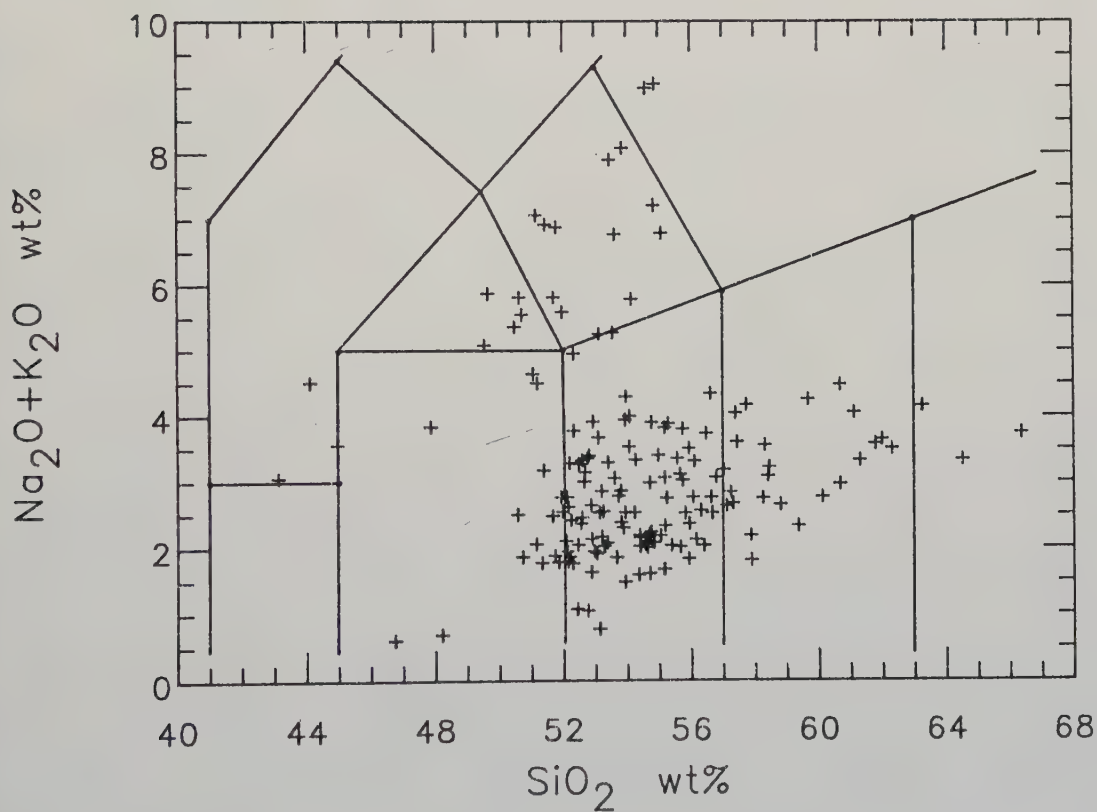
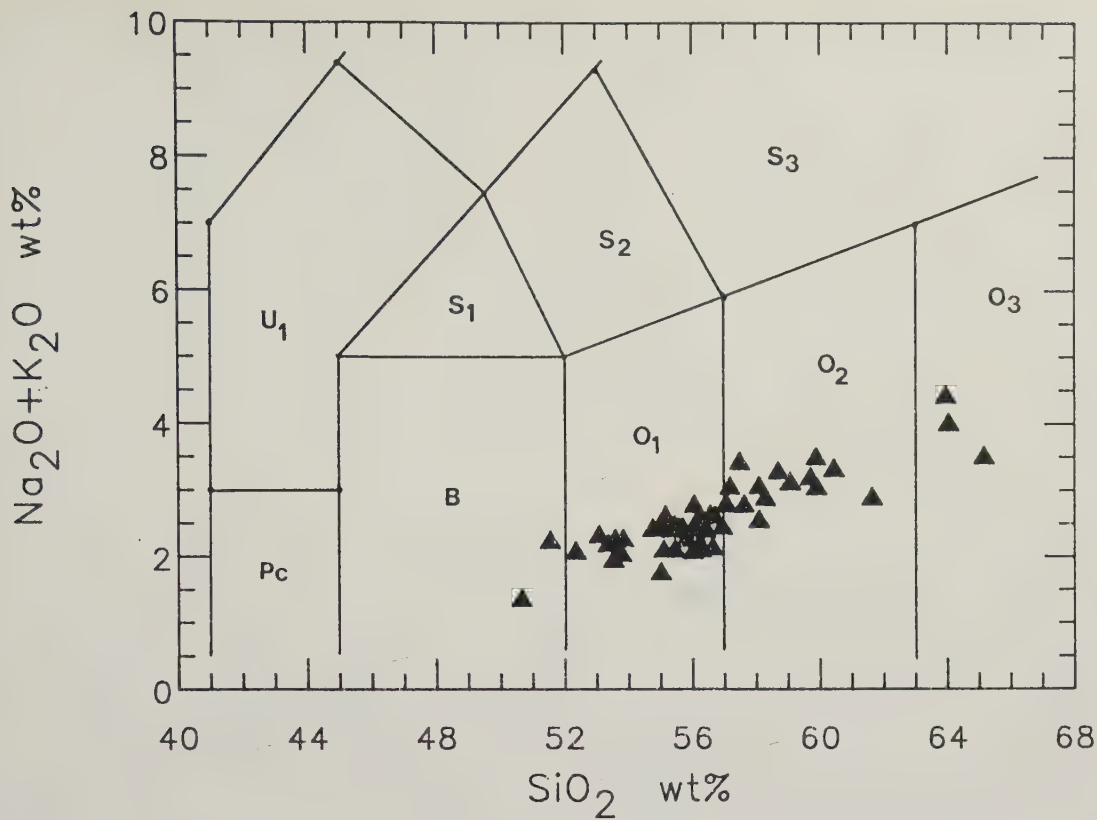


Fig. 4.10. TAS digaram for classification of igneous rocks. Glasses are triangles, whole rocks are crosses. Pc =microbasalt, B =basalt, O_1 =basaltic andesite, O_2 =andesite, O_3 =dacite, S_1 =trachybasalt, S_2 =basaltic trachyandesite, S_3 =trachyandesite, U_1 =basanite-tephrite. Glass compositions are well correlated, whereas whole rock compositions scatter.

ratio of greater than 0.2 (Saunders et al., 1980). These are Cs, Rb, K, Ba, Sr, Th, U, and Pb. The rare earth elements (REE) and Y strictly belong to the LFS elements, but will be treated separately as suggested by Saunders et al. (1980), because they resemble the HFS in their behaviour in some respects. Transition elements are Sc, Cr, Co, V and Ni, based on their similar behaviour and more compatible nature (distribution coefficients for crystal/liquid > 0.3 (Frey et al., 1978)).

Transition elements (Sc, Cr, Co, V, Ni). Sc and Co abundances in nine out of ten glasses lie between 30 and 38 (Fig. 4.11), the common range for relatively unfractionated basaltic and andesitic samples (Gill, 1981). The dacite (sample 353) has low concentrations of Co, Cr, and Sc. Cr and Ni abundances show an overall decrease with increasing FeO^*/MgO with especially high Cr and Ni contents in the olivine phenocryst-rich samples (Fig. 4.12, 4.13).

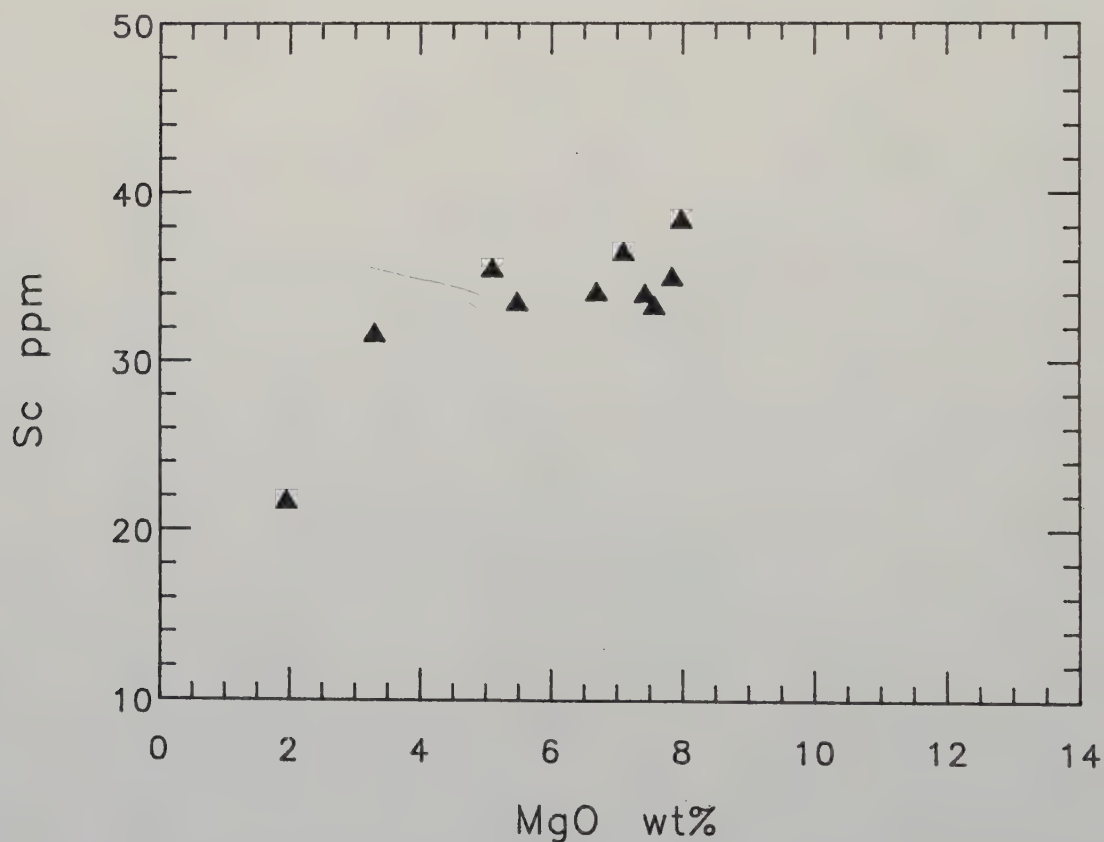


Fig. 4.11. MgO versus Sc for glasses (triangles).

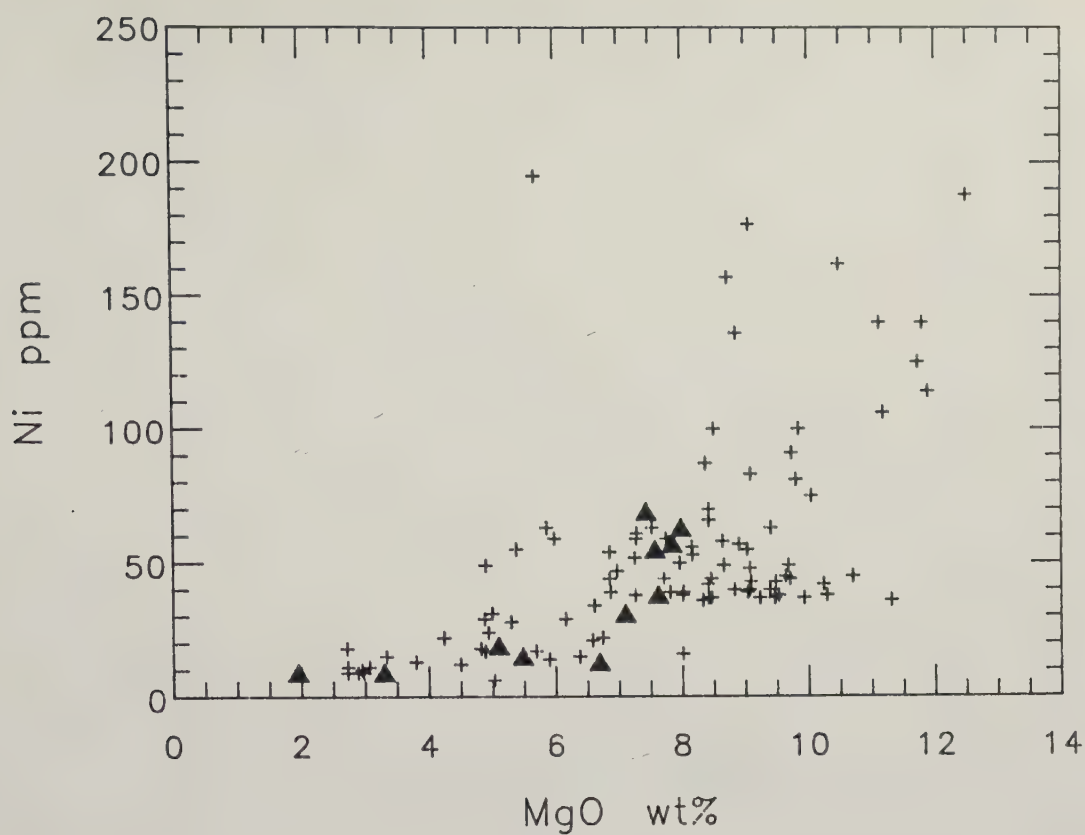


Fig. 4.12. MgO versus Ni for glasses (triangles) and whole rocks (crosses).

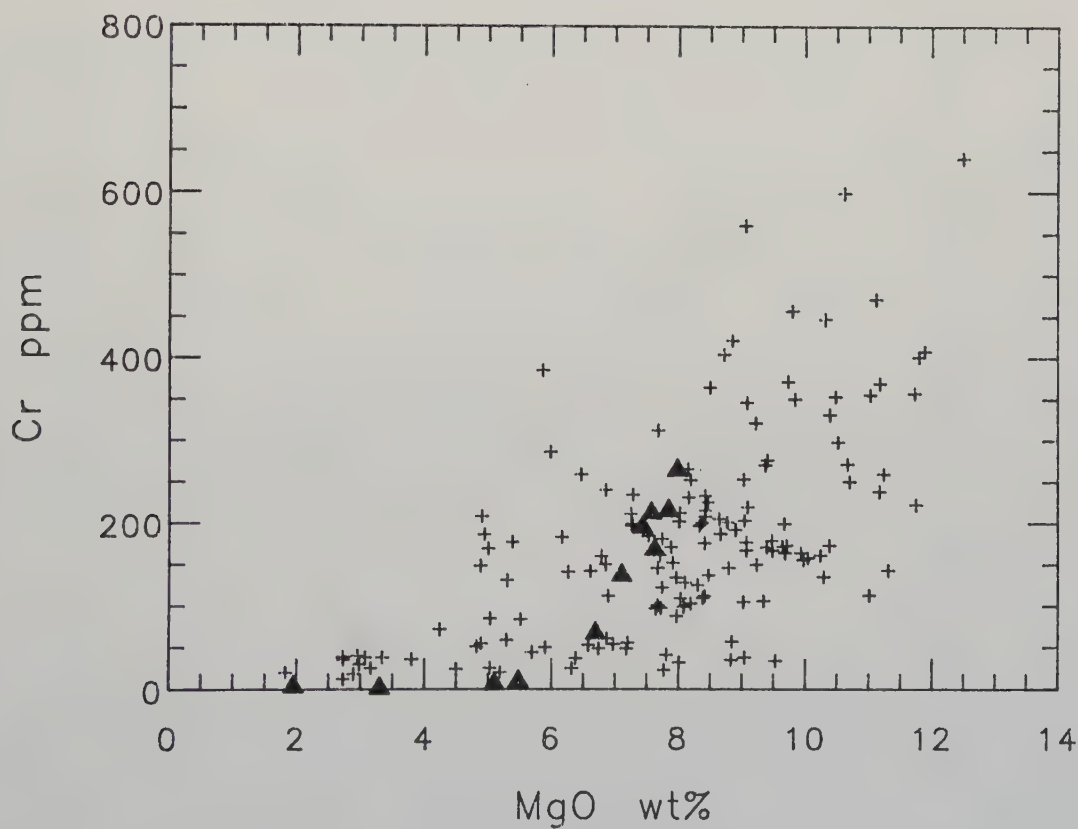


Fig. 4.13. MgO versus Cr for glasses (triangles) and whole rocks (crosses).

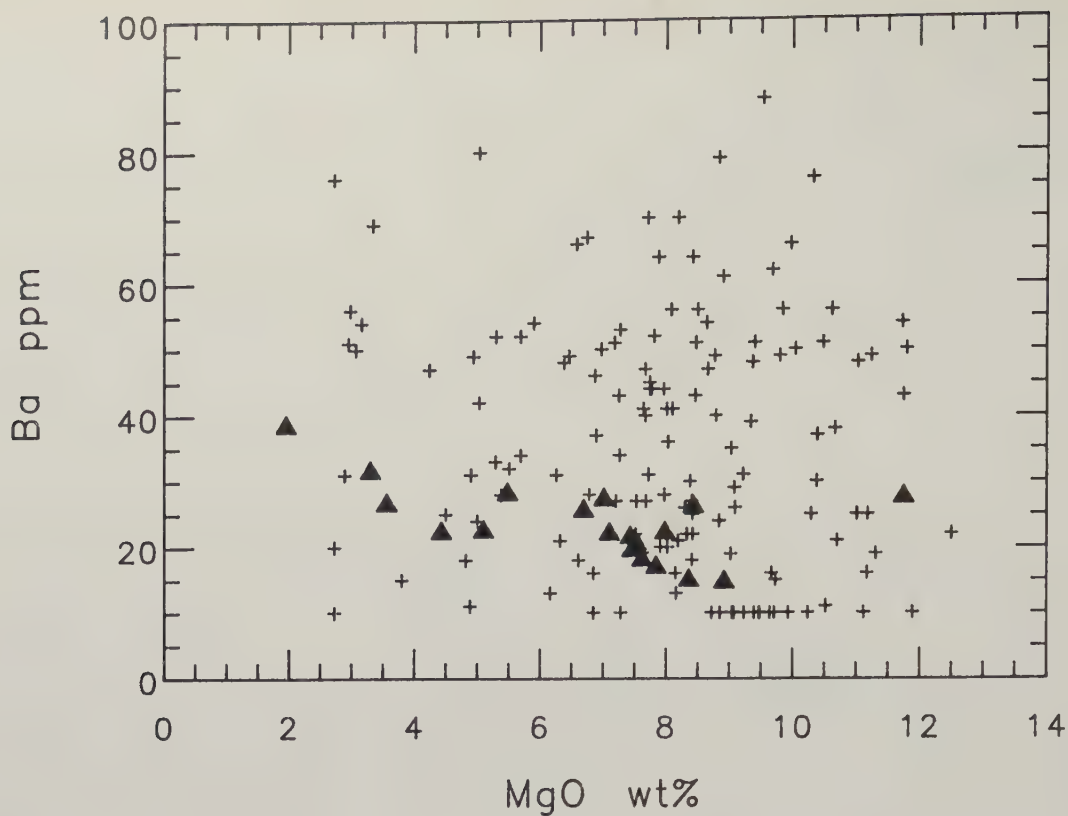


Fig. 4.14. MgO versus Ba for glasses (triangles) and whole rocks (crosses).

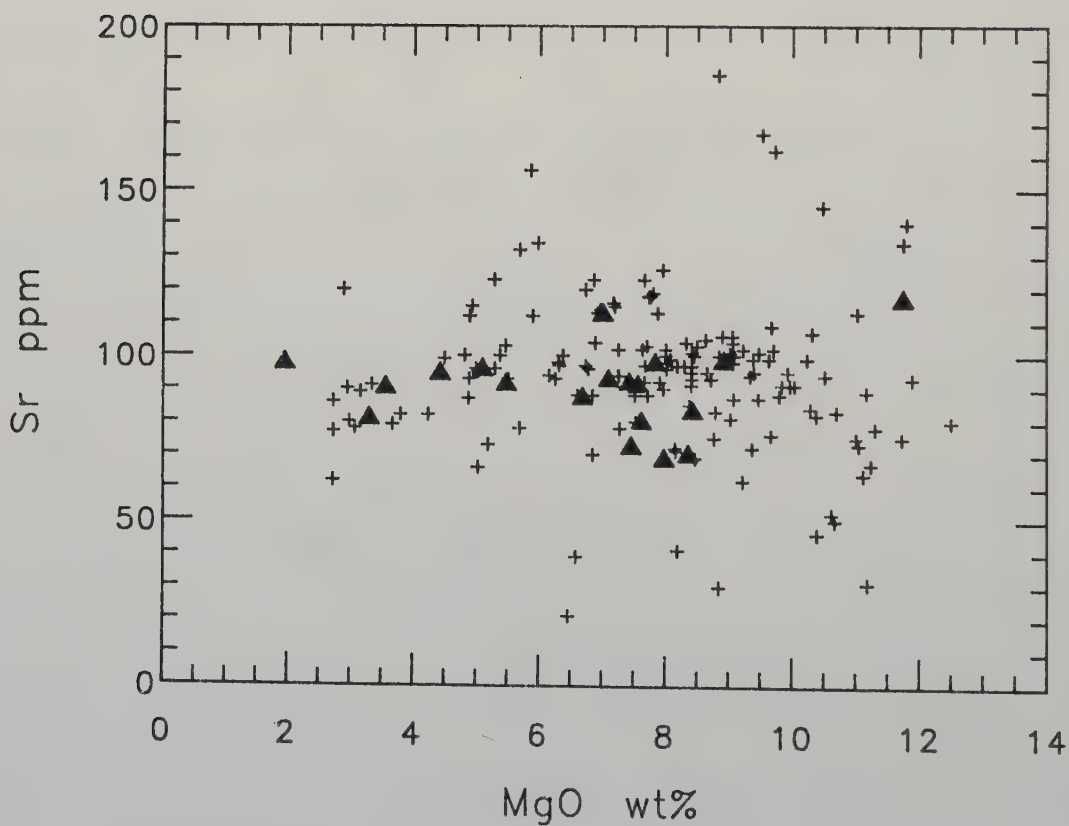


Fig. 4.15. MgO versus Sr for glasses (triangles) and whole rocks (crosses).

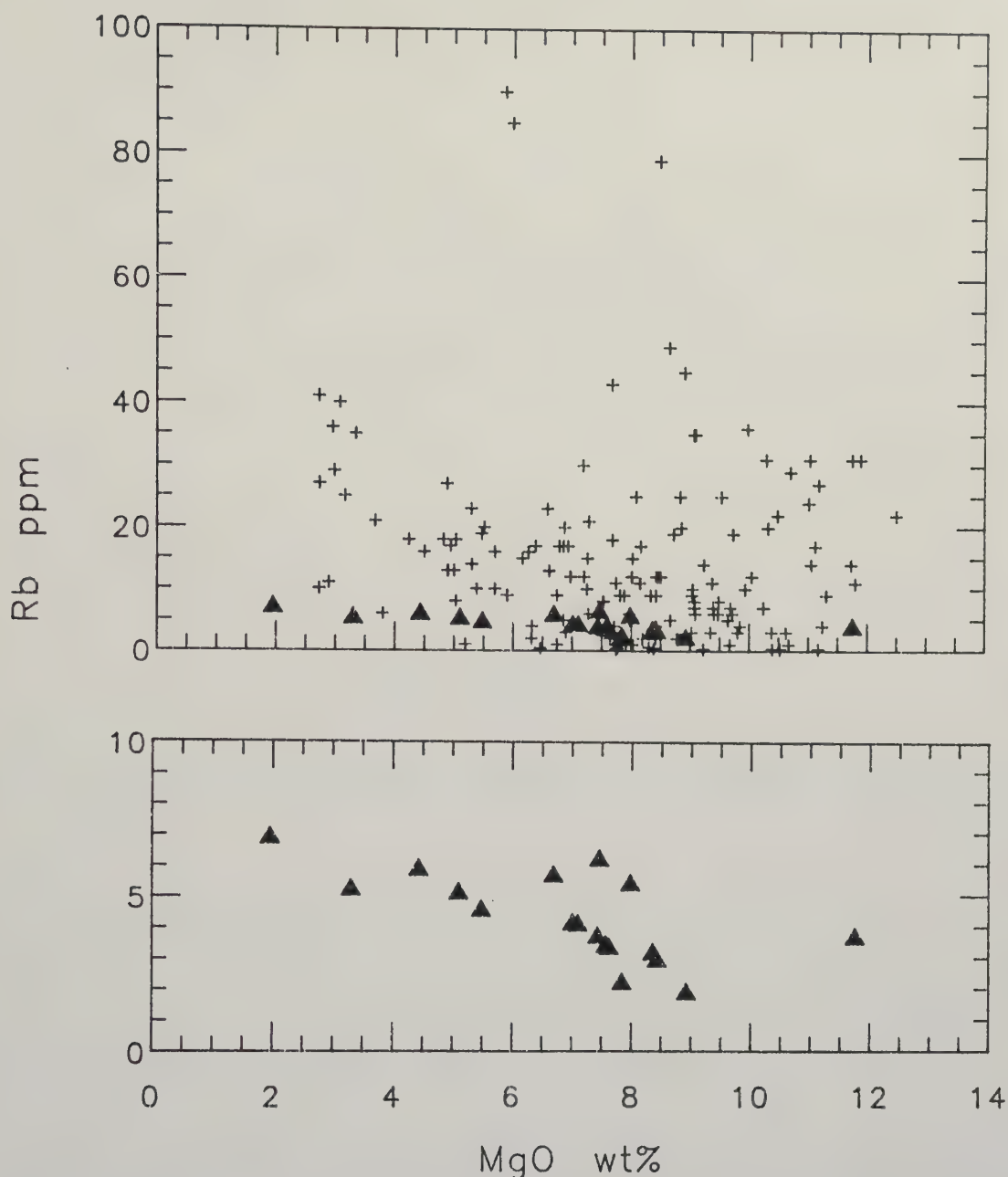


Fig. 4.16. MgO versus Rb for glasses (triangles) and whole rocks (crosses). The lower part of the diagram shows only glass separates analyzed by isotope dilution.

Low field strength elements (LFS) are K, Rb, Cs, Sr, Ba and Th. They show a restricted range of concentrations for the glass samples and a larger scatter for the whole rocks (Fig. 4.8, 4.14 - 4.16). K, Rb, Cs, Th and Ba increase with decreasing MgO, whereas Sr concentrations show no distinct trend (Fig. 4.8, 4.14 - 4.16).

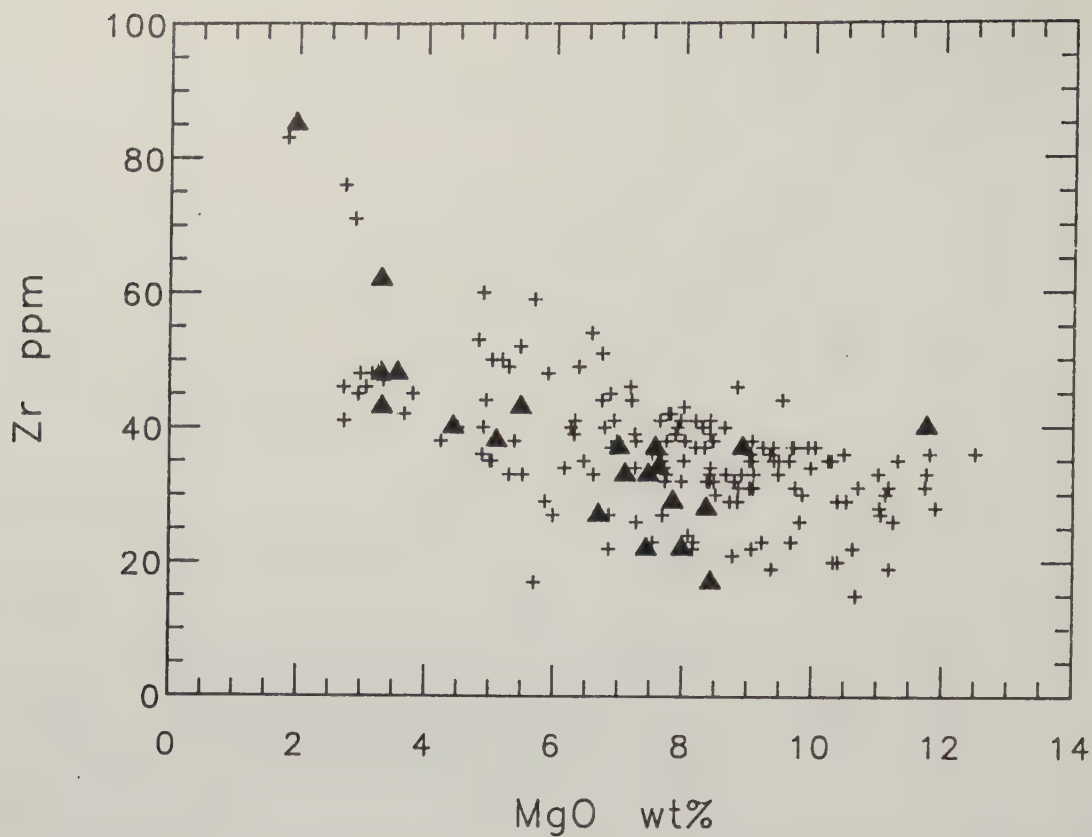


Fig. 4.17. MgO versus Zr for glasses (triangles) and whole rocks (crosses).

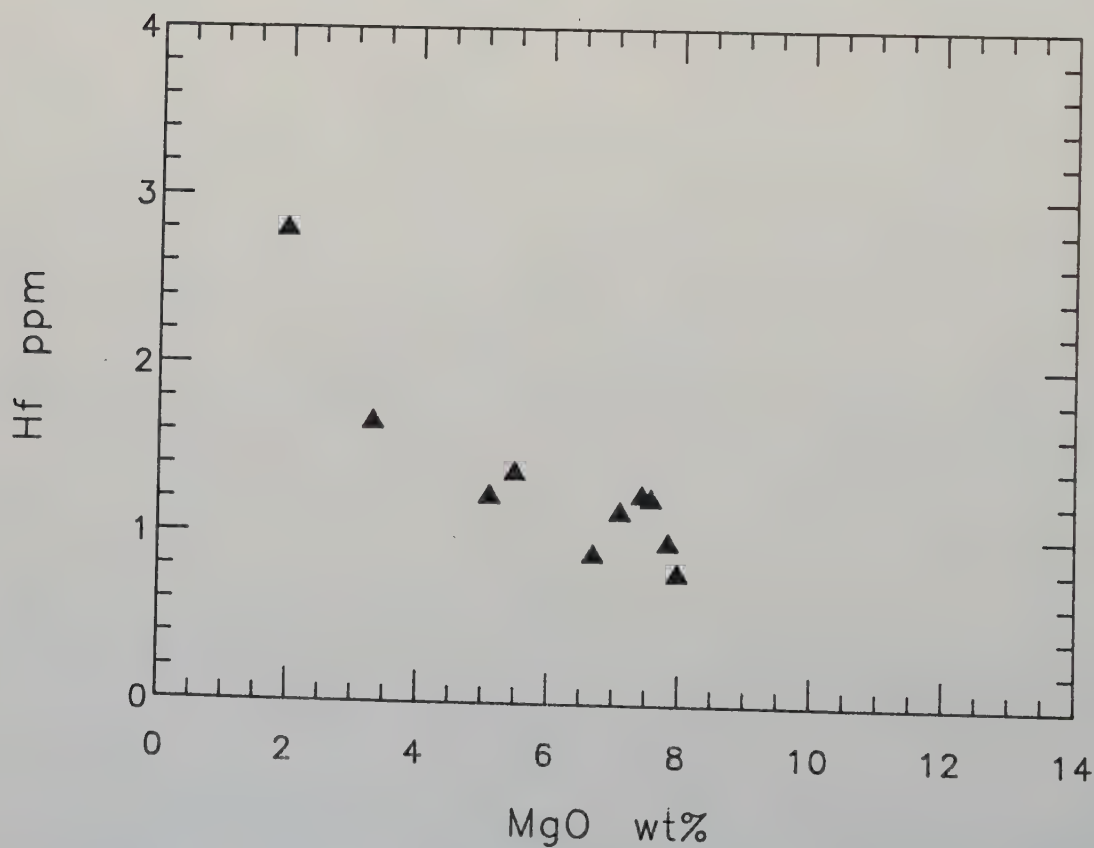


Fig. 4.18. MgO versus Hf for glasses (triangles)

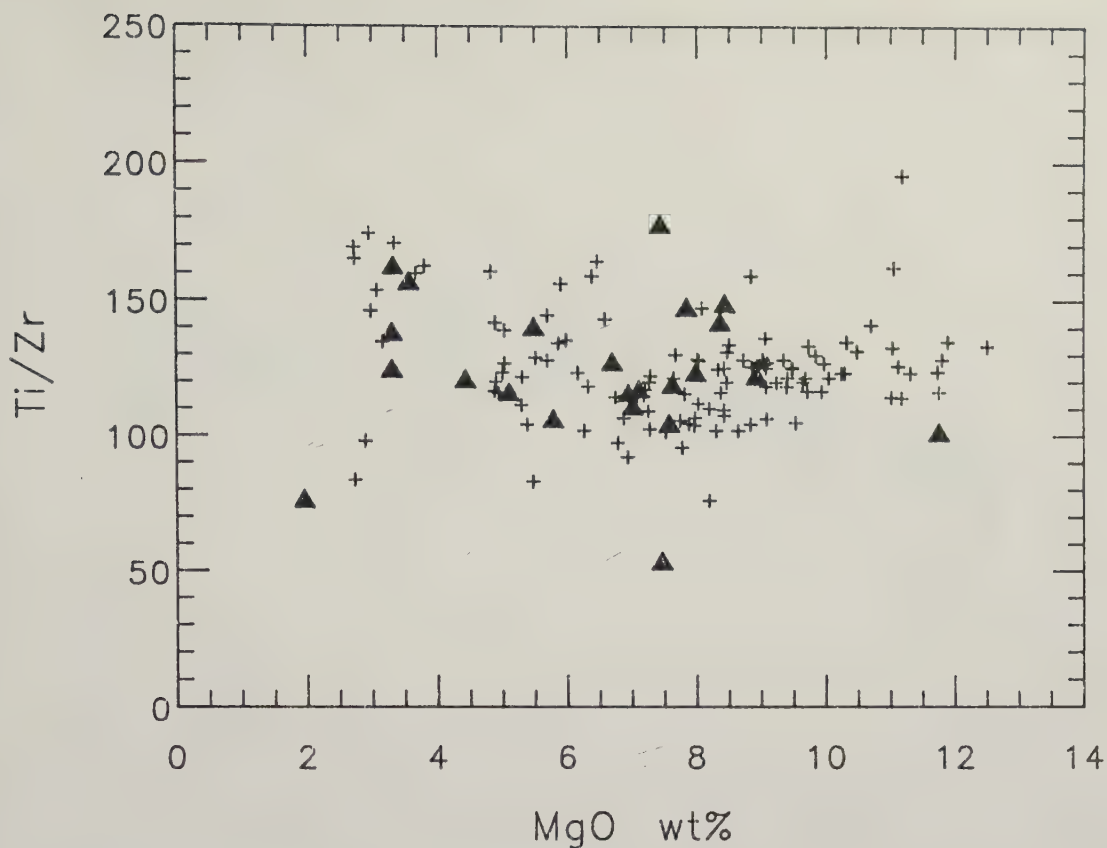


Fig. 4.19. MgO versus Ti/Zr for glasses (triangles) and whole rocks (crosses).

High field strength elements (HFS) (Ta, Ti, Hf, Zr, and Nb) abundances elements are low, and increase with decreasing MgO (Fig. 4.3, 4.17, 4.18). Ti/ Zr ratios range from 50 to 200, and show no correlation with MgO (Fig. 4.19).

Rare earth element (REE) concentrations (normalized to chondrites) are shown in Fig. 4.20 - 4.22 for glasses and whole rocks. The samples from the Akaki River section are characterized by light REE depletion ($\text{La}_N/\text{Yb}_N = 0.41 - 0.56$) and by a wide range of absolute abundances, from 3 to 6 x chondritic in a mafic sample to 20 x chondritic in the most differentiated sample (353). The patterns are nearly parallel, except that some patterns show slight (samples 315 and 345) positive La (or negative Ce) anomalies (Fig. 4.20). Samples KA and LIM show moderate positive La and negative Ce anomalies (Fig. 4.22). Because the Akaki River samples show very similar REE patterns, the Nd concentrations can be considered to be representative for all REE. Nd concentrations increase with decreasing MgO, but show a large variation and range from 2 to 7 ppm at 7% MgO (Fig. 4.23).

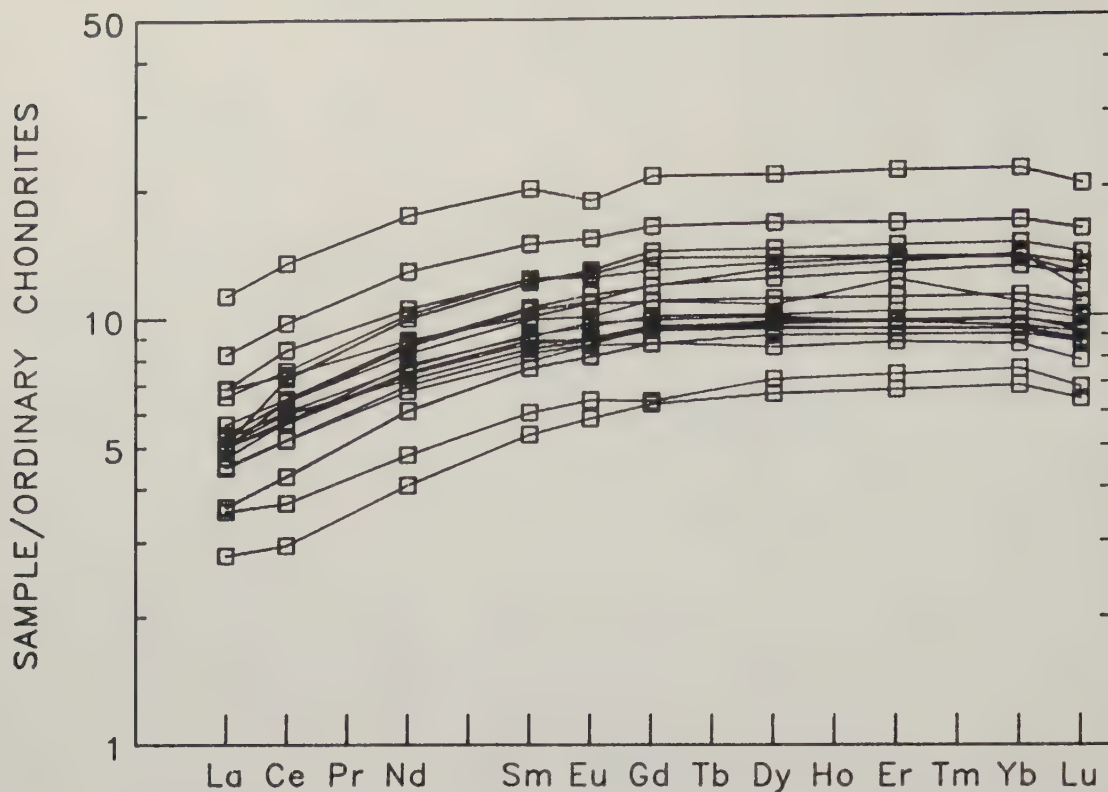


Fig. 4.20. REE concentrations (normalized to chondrites, Nakamura, 1974)) of glass samples from the Akaki river section.

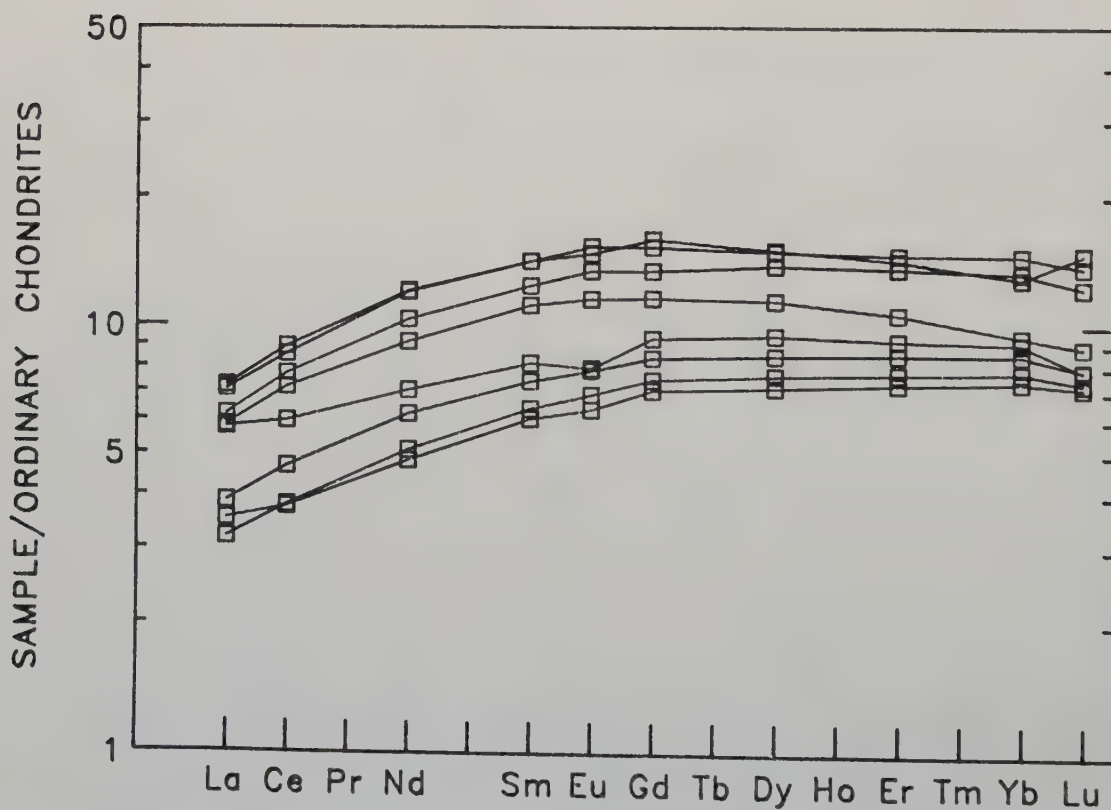


Fig. 4.21. REE concentrations (normalized to chondrites) of whole rock samples.

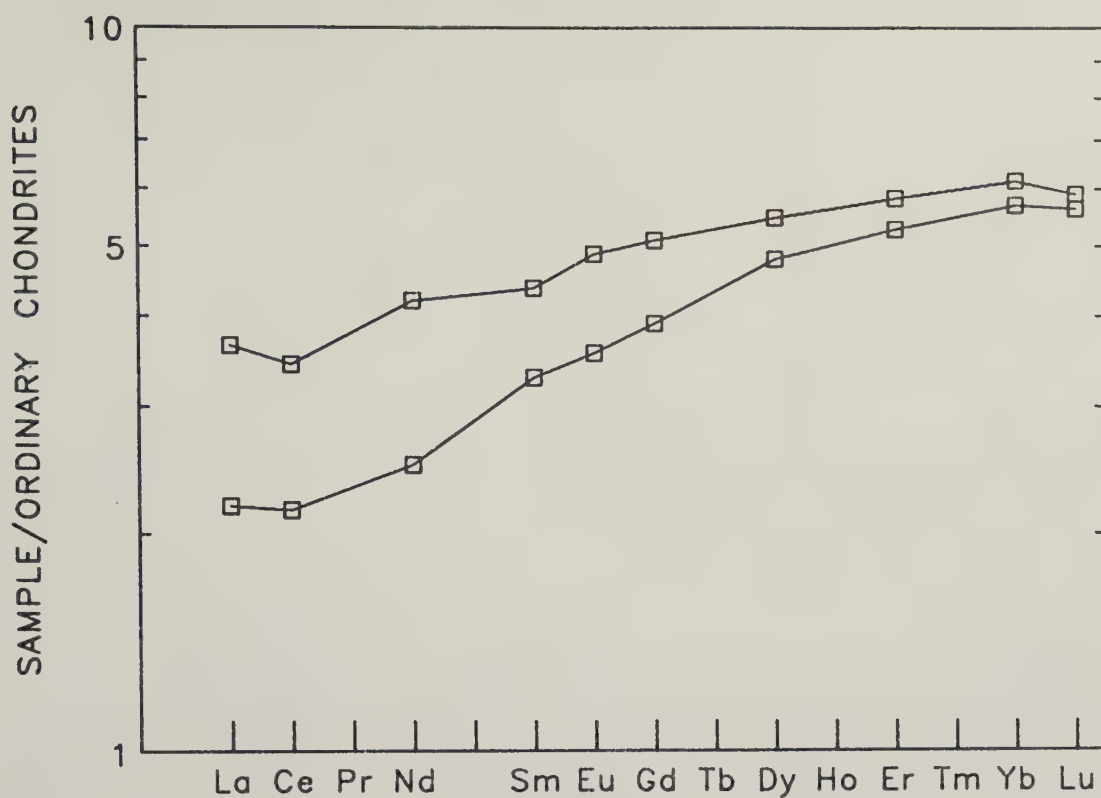


Fig. 4.22. REE concentrations (normalized to chondrites) of glass samples KA and LIM from Kalvasos and Limni.

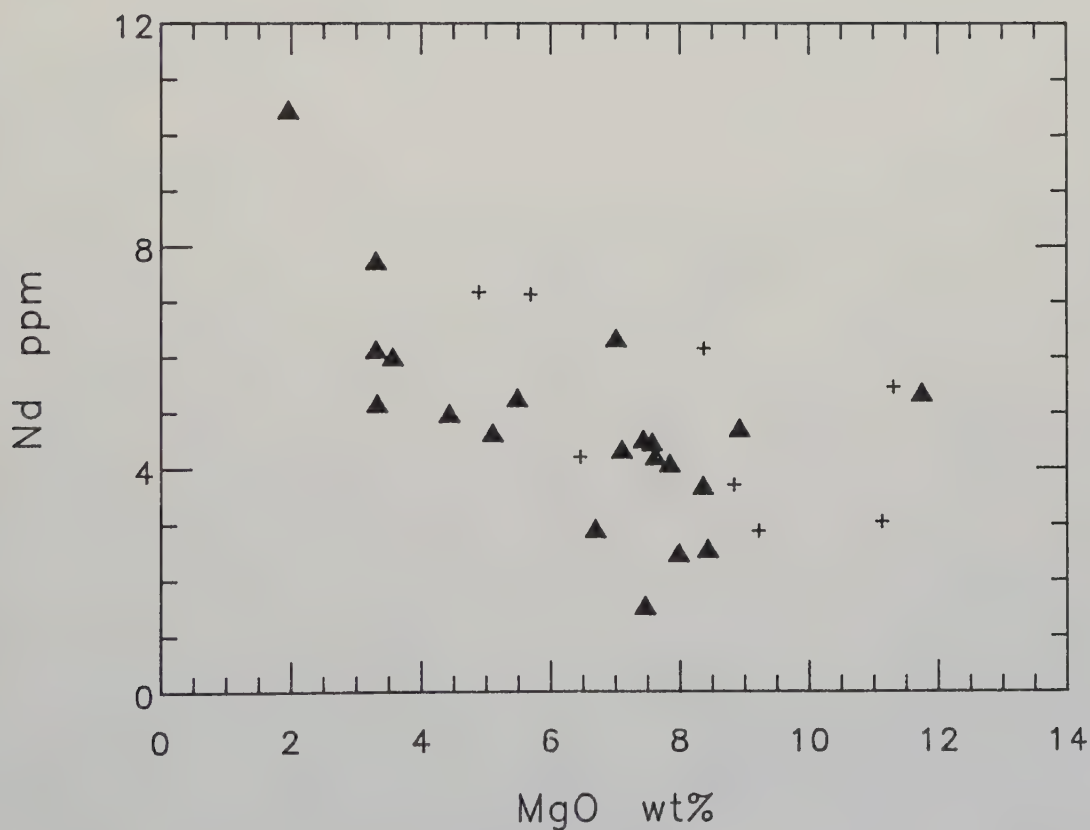


Fig. 4.23. MgO versus Nd for glasses (triangles) and whole rocks (crosses).

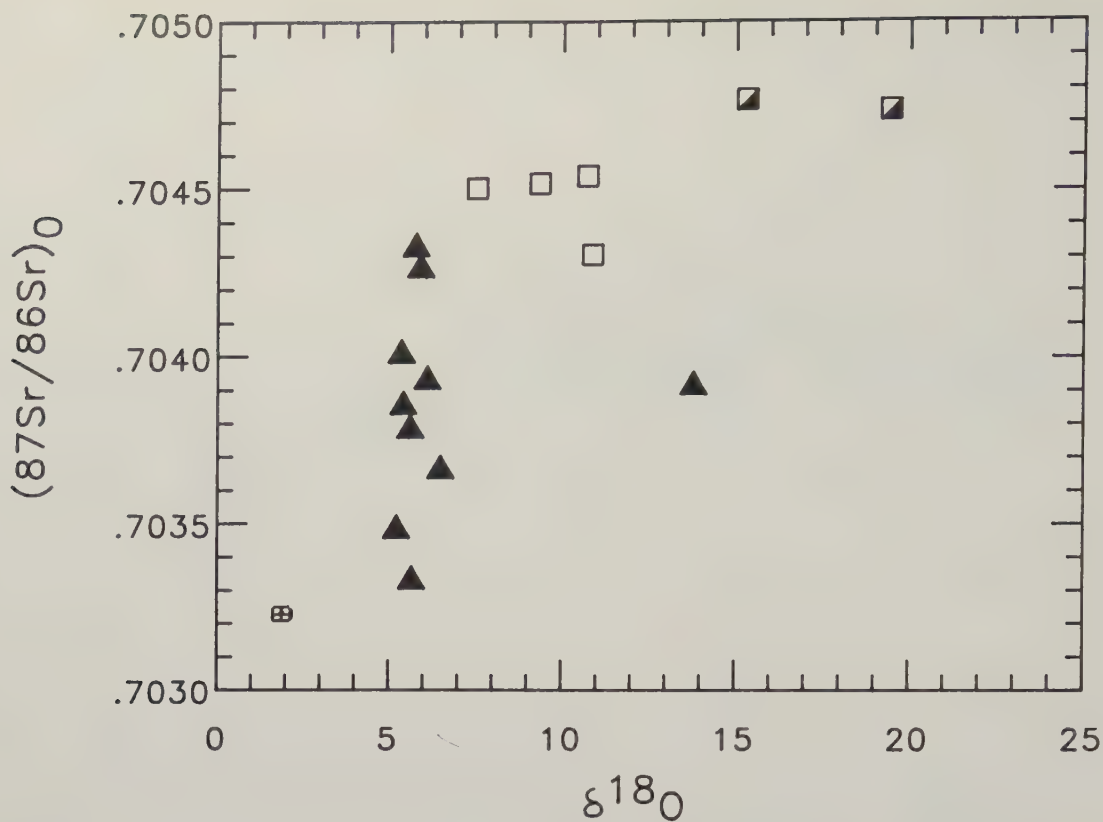


Fig. 4.24. $^{87}\text{Sr}/^{86}\text{Sr}$ (measured) versus oxygen isotopic composition for glass (full triangles), whole rocks (open squares) and altered glass (half-filled squares). Altered glass samples show higher ratios of $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ than whole rocks. Error bars are given.

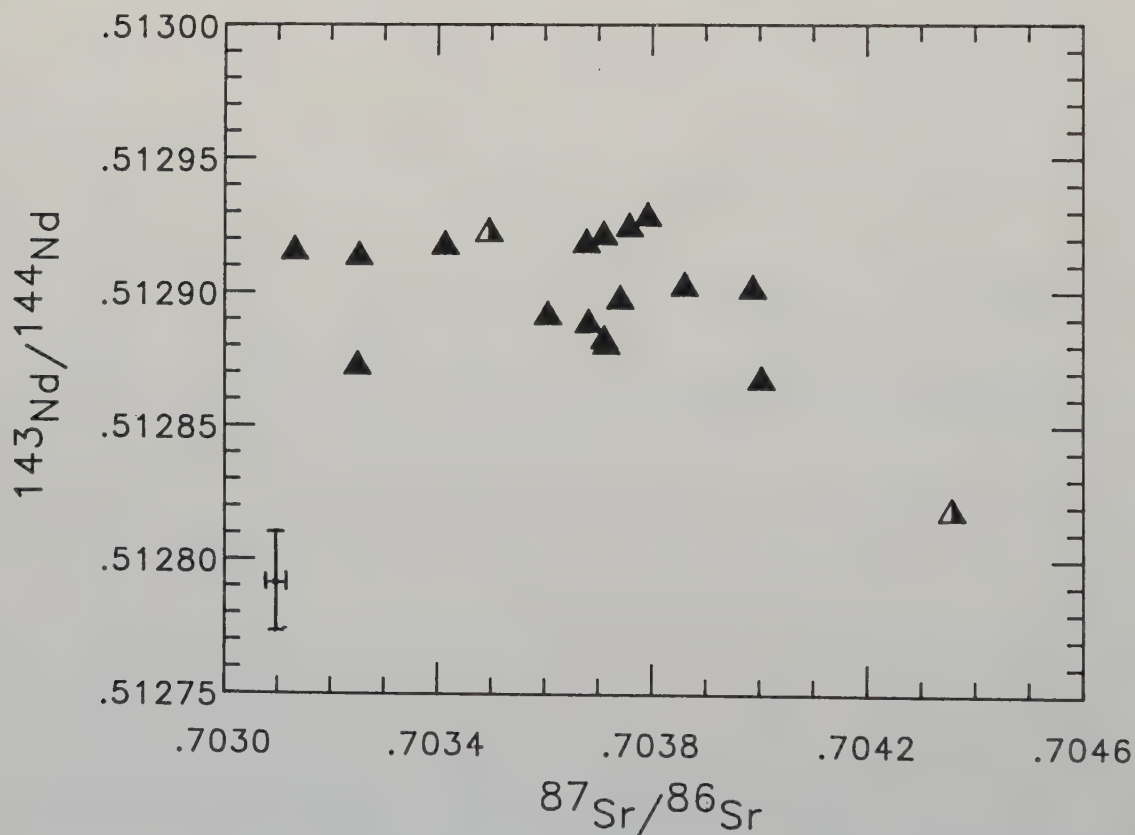


Fig. 4.25. Sr-Nd initial isotopic variations for Akaki glasses (solid triangles) and glass samples KA and LIM (half-filled triangles). Error bars are given.

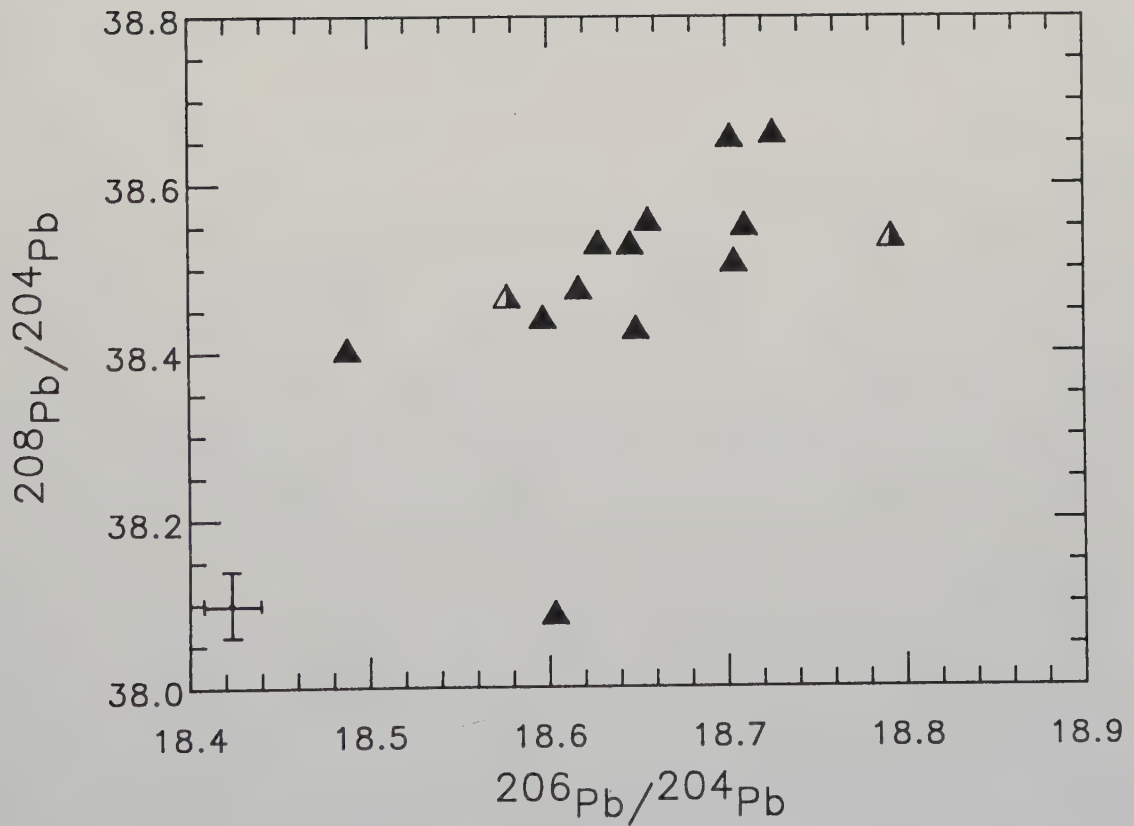
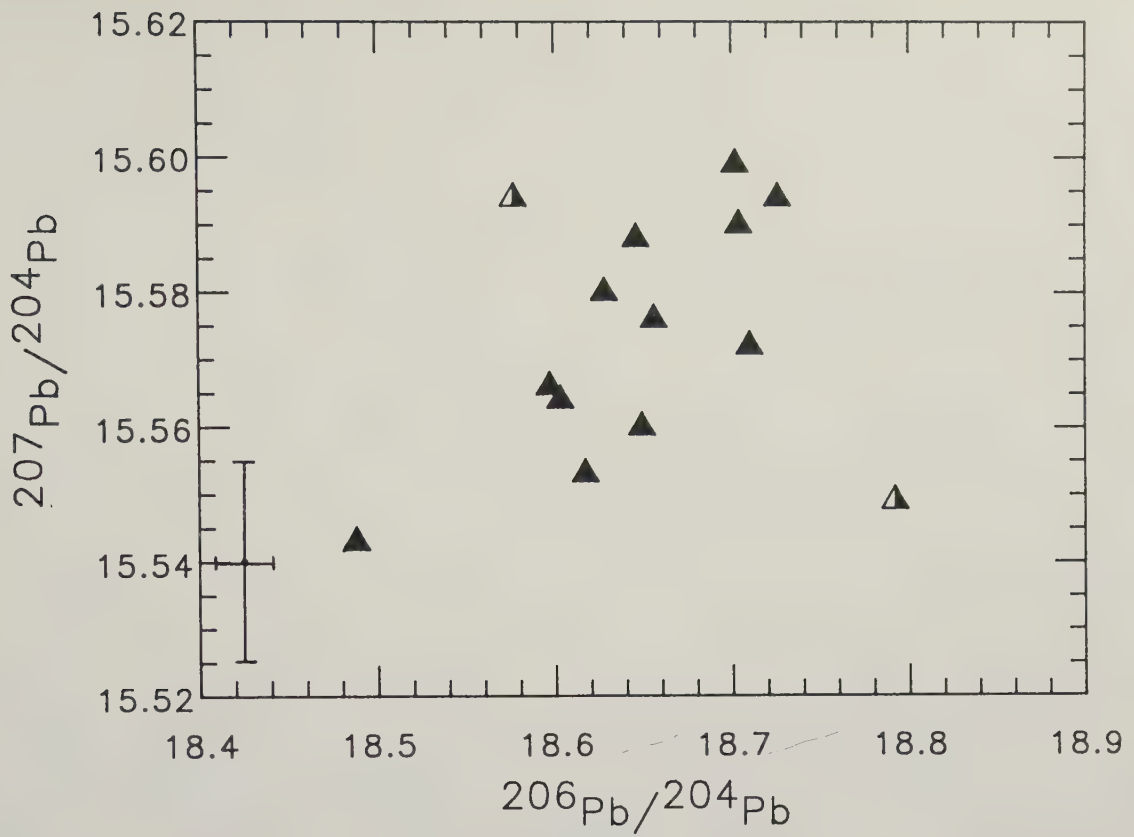


Fig. 4.26. Pb-Pb isotopic variations for Akaki glasses (solid triangles) and glass samples KA and LIM (half-filled triangles). Error bars are given.

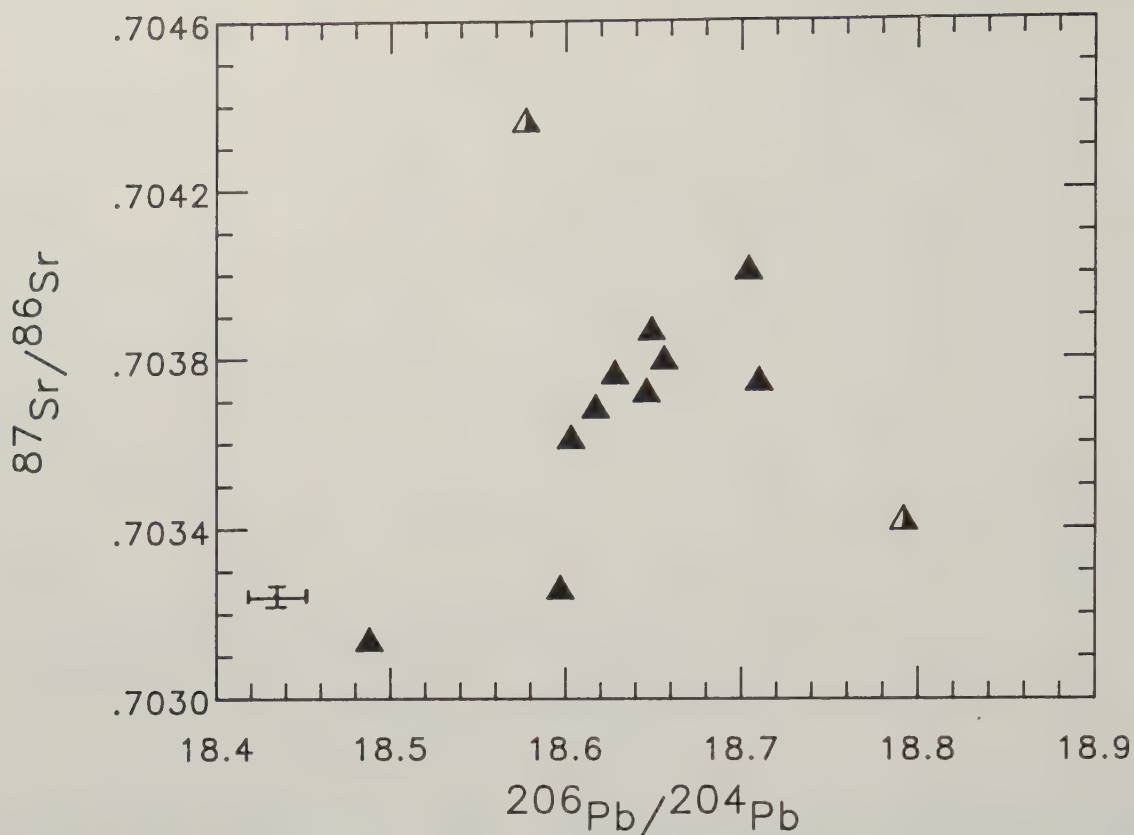


Fig. 4.27. Pb-Sr isotopic variations (Sr age-corrected) for Akaki glasses (solid triangles) and glass samples KA and LIM (half-filled triangles). Error bars are given.

4.3.3 ISOTOPIC COMPOSITIONS

Isotopic data for Sr, Nd, Pb, and O of glasses, altered glasses, and whole rocks from the Akaki River section and of glasses from other localities are given in Tables A.14, A.16, A.18 and Figures 4.24 - 4.27. The initial compositions of Sr and Nd have been calculated for an age of 80 Ma. Recently, Staudigel et al. (1986) determined an age of 86 Ma for secondary minerals of volcanics in the Troodos extrusive series. The differences between initial ratios for 80 and 86 Ma are within the errors of determination, thus the initial values are given for 80 Ma as in Rautenschlein et al. (1985). $^{87}\text{Sr}/^{86}\text{Sr}$ initial ratios of glasses from the Akaki range from 0.7031 to 0.7040, whereas sample LIM has a higher value of 0.7044. Whole rock Sr isotopic compositions range up to 0.7048 (Fig. 4.24). $^{87}\text{Rb}/^{86}\text{Sr}$ ratios are also variable but do not correlate well with the present or initial $^{87}\text{Sr}/^{86}\text{Sr}$ ratios. The age-corrected $^{143}\text{Nd}/^{144}\text{Nd}$ ratios of Akaki samples range from 0.51287 to 0.51292, whereas sample LIM has a ratio of 0.51282. The corresponding variation of $\epsilon_{\text{Nd}}(\tau=80\text{Ma})$ is from +5.5 to +7.6, which is

slightly larger than the analytical error. There is a slight negative correlation between initial Sr and Nd isotopic composition (Fig. 4.25). There is only a small variation in Pb isotopic composition, particularly when compared with that observed in Sr. No age correction has been made for the Pb isotopic composition, because U and Pb concentrations were not determined. Pb isotopic ratios from the Akaki River section correlate with each other and also with Sr isotopic ratios (Fig. 4.26, 4.27), whereas samples KA and LIM do not follow these trends.

Ten out of eleven glass samples show a restricted range of oxygen isotopic composition ($\delta^{18}\text{O} = 5.4 - 6.5$ with a mean of 5.8 ± 0.4 (1 sigma, $n = 10$)). These values are in the range reported for mantle derived volcanics (Ito et al. 1987). One glass (sample 353) has a $\delta^{18}\text{O}$ of 13.8 and is thus enriched in ^{18}O relative to the other glasses by 8 ‰. Whole rock and altered glass samples show similarly high oxygen isotopic ratios, but higher $^{87}\text{Sr}/^{86}\text{Sr}$ than the glasses (Fig. 4.24).

CHAPTER 5. CHEMICAL ALTERATION

5.1 INTRODUCTION

The alkali content of volcanic rocks is widely used to classify these rocks, e.g by using the Total Alkali Silica diagram (Fig. 4.10) (Le Bas et al., 1986). It is based on Na_2O , K_2O , and SiO_2 in fresh volcanics. Furthermore, the chemistry of volcanic rocks is used for interpretations of genetic relationships, magma genesis, or tectonic setting. These interpretations are questionable or meaningless if secondary alteration has changed the primary chemical compositions of the rocks.

Some elements are more sensitive to this process than others. During secondary alteration of submarine volcanics by interaction with seawater the H_2O , Fe_2O_3 , K_2O , Rb, Cs, Ba and U concentrations and Sr and O isotopic ratios may increase drastically, whereas CaO , and MnO , are lost from the fresh rocks. In contrast, SiO_2 , Al_2O_3 , FeO^* , Th, Zr, Hf and the REE are much more resistant to alteration, and this is also true for the Nd and Pb isotopic ratios (Honnorez, 1967, Robinson et al., 1977, Tatsumoto, 1978, Staudigel et al., 1981a,b, Staudigel & Hart, 1983, Thompson, 1983, Faure, 1986). This general pattern of element behaviour is borne out by the present analyses.

The lavas of the Troodos ophiolite have undergone low temperature seawater alteration (e.g. Spooner et al., 1974, Spooner, 1977, Pearce, 1975, Gillis & Robinson, 1985), but fresh volcanic glasses are also preserved in the extrusive series of the Troodos ophiolite. This is quite unusual for volcanics of Cretaceous age. It opens the unique opportunity to obtain information about the primary compositions of these volcanics. These data can be used to interpret the genetic relationships, magma genesis and tectonic setting of the lavas. Furthermore, the chemistry of the fresh glasses can be compared to corresponding whole rocks and altered glasses. This will allow an assessment of the degree of alteration of the whole rocks in the extrusive series and a judgement to what extent the whole rock data represent primary compositions.

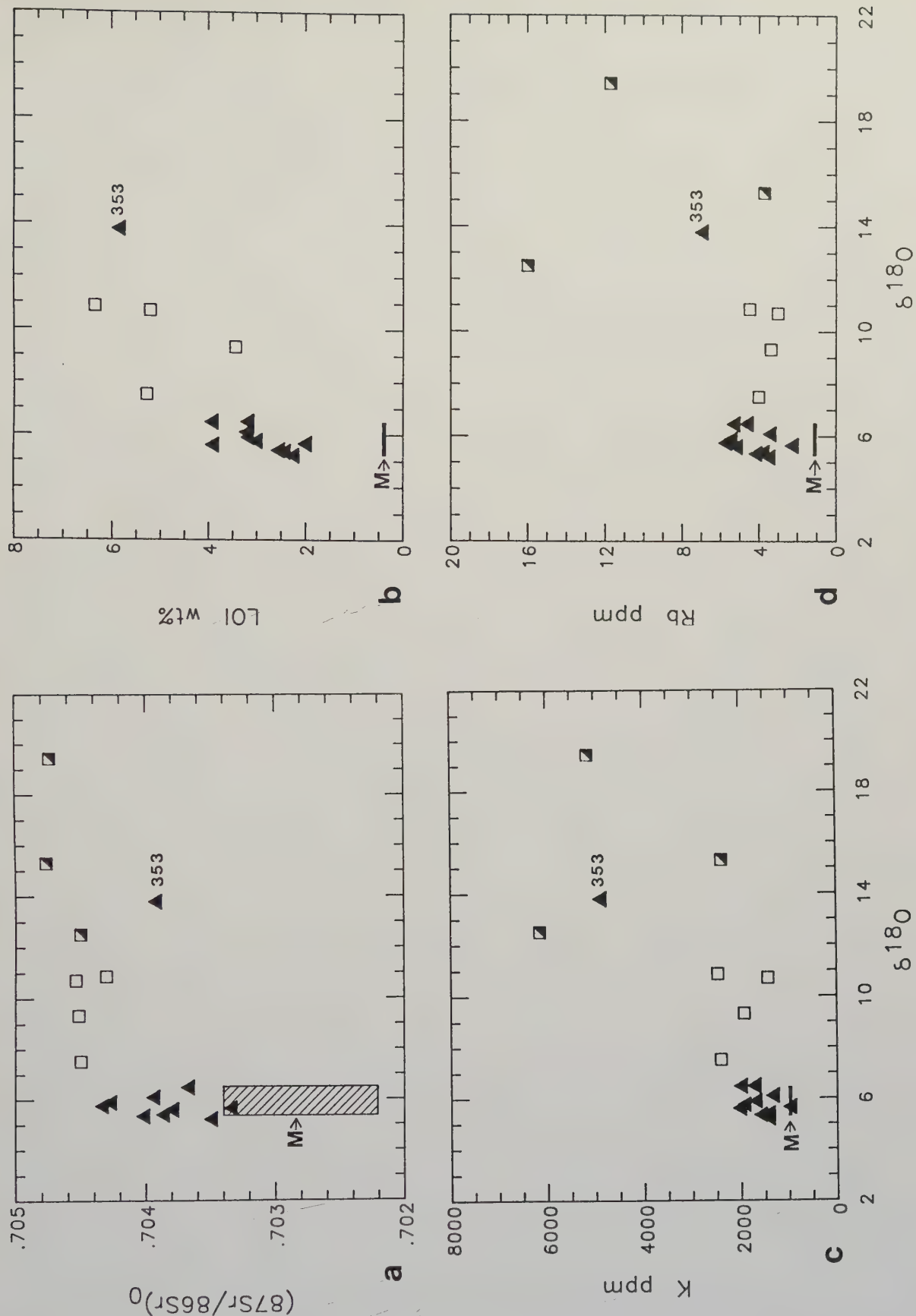


Fig. 5.1. K, Rb, $^{87}Sr/^{86}Sr$ (measured), and loss on ignition (LOI) versus oxygen isotopic composition for glass separates (full triangles), whole rocks (open squares), and altered glasses (half-filled squares). The number '353' refers to the anomalous glass sample. Reference field for MORB (M) from Ito et al. (1987), Morris & Hart (1983), Jochum et al., 1983, 1986.

5.2 FRESHNESS OF THE GLASS SAMPLES

In order to assess the freshness of the glass samples, the trace elements and isotopic ratios most sensitive to alteration will be considered. If these elements, such as the alkali and alkaline earth metals, and Sr and O isotopic compositions represent primary compositions, the glasses may be regarded as fresh. Only then their chemical compositions will be used for interpretations of genetic relationships, magma genesis, and tectonic setting.

During seawater hydrothermal alteration of modern oceanic basalts, the isotopic ratios of oxygen and Sr increase from their primary MORB values between +5.35 to +6.47 (Ito et al., 1987) and $0.7028 \pm .0002$ (Morris & Hart, 1983), respectively. The abundances of alkali elements and volatiles will also generally increase during low temperature alteration. These changes are due to decomposition of groundmass glass and precipitation of secondary minerals containing high concentrations of these elements and high isotopic ratios of Sr and oxygen, e.g. smectite, calcite, zeolites, and celadonite (Taylor, 1968, Hart, 1971, Hart & Staudigel, 1982, Muehlenbachs & Clayton, 1972 a,b, 1976, Staudigel et al. 1981a,b, 1983, Boehlke et al., 1984). Initial $^{87}\text{Sr}/^{86}\text{Sr}$ values will increase towards the limiting value of seawater (Cretaceous seawater $^{87}\text{Sr}/^{86}\text{Sr} = 0.7074$, Burke et al. 1982).

The variation in $\delta^{18}\text{O}$, K, Rb, volatiles (LOI = loss on ignition) and $^{87}\text{Sr}/^{86}\text{Sr}$ for glasses, altered glasses and whole rocks is illustrated in Figure 5.1. Fields for N-MORB compositions are also given. Ten of eleven glasses show a restricted range of oxygen isotopic composition ($\delta^{18}\text{O} = 5.4$ to 6.5) with a mean $\delta^{18}\text{O}$ of 5.8 ± 0.5 (1 sigma, $n = 10$), $^{87}\text{Sr}/^{86}\text{Sr}$, and LOI, K and Rb concentrations, whereas one glass, sample 353 shows higher $\delta^{18}\text{O}$, K, and Rb, but $^{87}\text{Sr}/^{86}\text{Sr}$ within the range of the other glasses. These glass data show no correlation between $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$.

In contrast, altered glasses and whole rocks show high $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ as well as high K and Rb, suggesting that low temperature alteration has affected their chemistry (Fig. 5.1). The larger increase in $^{87}\text{Sr}/^{86}\text{Sr}$, $\delta^{18}\text{O}$, K and Rb indicates that the degree of alteration is higher for altered glass than for whole rocks.

One glass, sample 353, has a $\delta^{18}\text{O}$ of 13.8 and is thus enriched in ^{18}O relative to all other glasses by 8 ‰. This sample is compositionally distinct from the others. It is higher in SiO_2 (64%) and in incompatible element concentrations (except for Sr), lower in MgO and compatible trace elements, and it has a negative Eu anomaly. Thus it shows all the characteristics of extensive fractional crystallization. However, fractional crystallization alone cannot account for the observed drastic increase in $\delta^{18}\text{O}$. Muehlenbach & Byerly (1982) have shown that 90% fractional crystallization leads to enrichment of only 1 to 3 ‰ $\delta^{18}\text{O}$ in the residual melt. Sample 353 is also different from the other glasses in terms of elevated loss on ignition (5.82 % versus a mean of 3.0 ± 1.16) and K (4850 ppm versus a mean of 1543 ± 372) (Fig. 5.1). Otherwise, like all of the glasses it is apparently fresh, being black, hard, and vitreous, with no developments of smectite or any of the characteristics of palagonite alteration. It also has a $^{87}\text{Sr}/^{86}\text{Sr}$ ratio within the range of the other glass samples (Figure 5.1), in contrast to the altered glasses which show high $^{87}\text{Sr}/^{86}\text{Sr}$.

In the case of sample 353, a fresh appearance cannot be considered absolute proof that the magmatic chemistry is preserved. It is conceivable that glass 353 underwent low temperature exchange of oxygen with seawater and an increase of loss on ignition and K, whilst retaining a vitreous state. However, this would have occurred without significant exchange of Sr isotopes, and this is not consistent with the observations on the altered glass samples (Fig. 5.1). Another, perhaps more likely possibility is that this change was caused by incorporation of altered rock into the magma during fractionation, in which case this glass may be fresh. It cannot be decided on the basis of evidence from a single sample if sample 353 was altered by interaction with seawater despite its fresh appearance or whether it was contaminated prior to eruption. Therefore sample 353 will not be considered in further discussion of alkali elements and Sr and O isotopic compositions.

The $\delta^{18}\text{O}$ values of the remainder of the glasses are within the range of those normally found in fresh ocean floor tholeiites (+5.35 to +6.47, Ito et al., 1987). Two glasses, samples 368 and 370) are at the upper limit of this range. Fresh alkali basalts and other silica

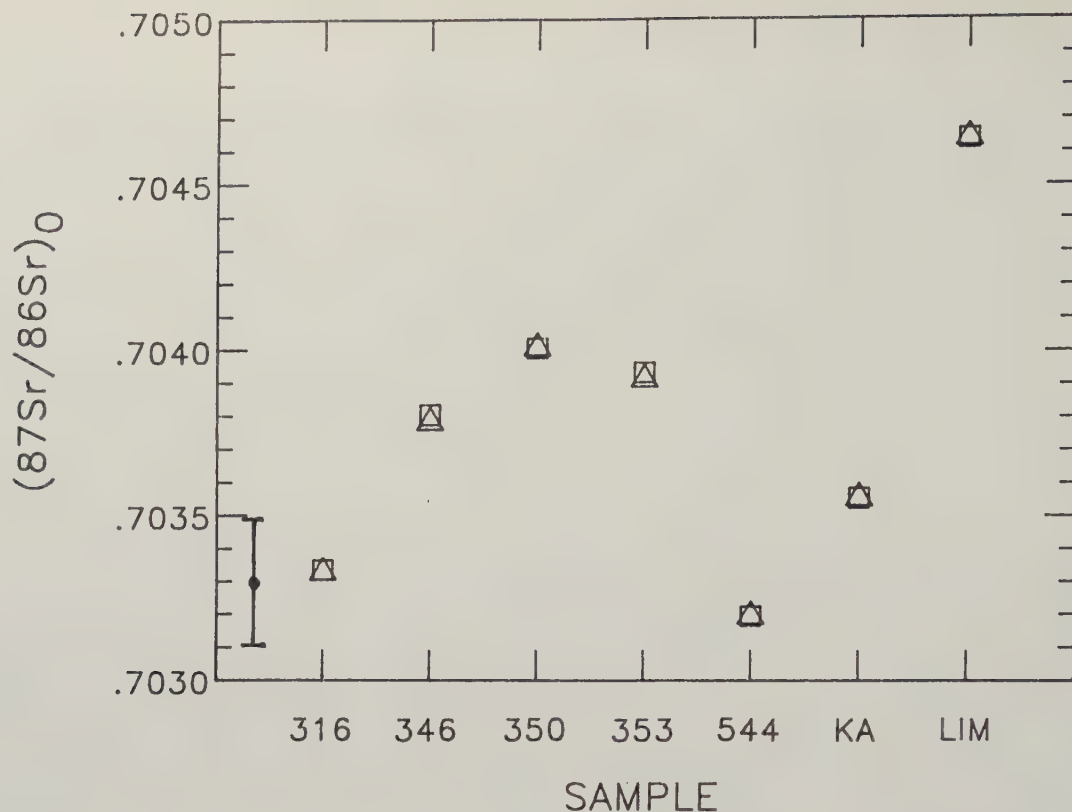


Fig. 5.2. $^{87}\text{Sr}/^{86}\text{Sr}$ (measured) of unleached (triangles) and leached (squares) portions of the same glass separates give identical results. Error bar is given.

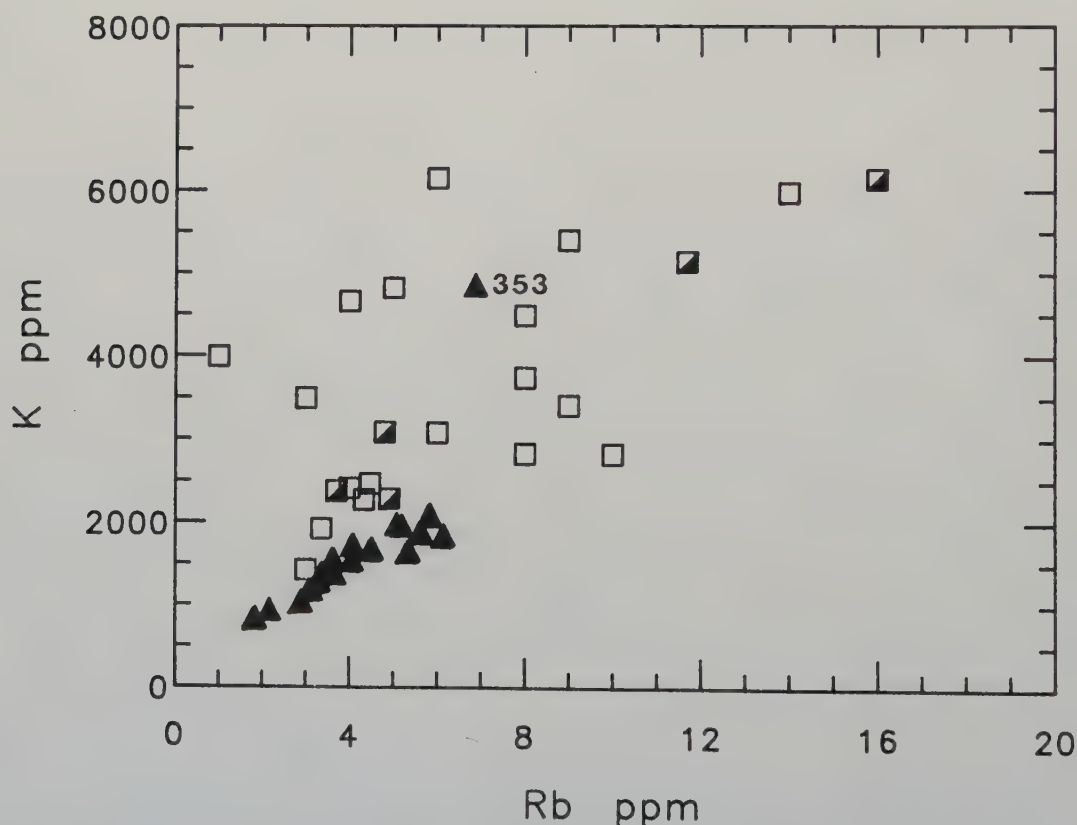


Fig. 5.3. Rb versus K in glass separates (full triangles), whole rocks (open squares), and altered glasses (half-filled squares). Altered glasses and whole rocks show strong enrichment of Rb and K compared to fresh glasses.

undersaturated basaltic rocks can be significantly enriched in ^{18}O relative to ocean floor tholeiites, with $\delta^{18}\text{O}$ up to 7 (Anderson et al. 1971; Kyser & O'Neil, 1978; Kyser et al. 1982, Graham & Harmon, 1983, Ito et al., 1987). Fractional crystallization can also increase $\delta^{18}\text{O}$ values (up to 1 to 3 ‰) (Muehlenbachs & Byerly, 1982), and samples 368 and 370 are fractionated. Thus ten of the eleven Troodos glasses have oxygen isotopic compositions within the range reported for fresh mantle derived volcanics.

$^{87}\text{Sr}/^{86}\text{Sr}$ of the Troodos glasses range from 0.7032 to 0.7044 (measured ratios). Sr isotopic compositions were determined on leached and unleached portions of the same samples and gave identical results (Fig. 5.2) (Table A.14). The results of the leaching experiments, and the close similarity of $\delta^{18}\text{O}$ to primary, unmodified mantle oxygen isotope values as well as the lack of correlation between $\delta^{18}\text{O}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ strongly suggest that the variation in $^{87}\text{Sr}/^{86}\text{Sr}$ is a primary feature of all these glasses (including sample 353).

K and Rb concentrations of all glasses except sample 353 show a good correlation and a relatively small variation (Fig. 5.3), whereas the altered glasses and whole rocks show a larger scatter, suggesting all glasses apart from sample 353 are fresh.

Volatile concentrations of the glasses range from 2 to 5 % (Fig. 5.1). These values are substantially higher than those found in MORB glasses (ca. 0.3 %), but overlap with those reported for glasses and glass inclusions (1 to 4 %) of back arc and island arc volcanics (Garcia et al., 1979; Muenow et al., 1980; Gill, 1981). Garcia (pers. comm) determined the volatile compositions of sample 316 (Table 7.2). The sample was degassed and released the volatiles at high temperatures, consistent with the behavior of fresh, unaltered glass. Thus, the volatile content of 2.29 wt% for this sample is primary, indicating the high volatile contents of the other glasses represent primary concentrations as well.

$\text{Fe}_2\text{O}_3/\text{FeO}$ ratios in the glasses range from 0.1 to 0.28, with a mean value of 0.19 ± 0.06 . These values are within the range of those reported for unoxidized andesites ($\text{Fe}_2\text{O}_3/\text{FeO} < 0.5$, Gill, 1981).

In summary, all glass samples except sample 353 show a restricted range of K and Rb concentrations, identical $^{87}\text{Sr}/^{86}\text{Sr}$ on leached and unleached portions of the same sample, volatile contents and $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios within the range of fresh andesites, and $\delta^{18}\text{O}$ values within the range reported for fresh, mantle derived volcanics. The chemistry of the glasses is thus interpreted to represent primary compositions for these alteration sensitive trace element concentrations and isotopic ratios. Therefore, all other less alteration-sensitive elemental and isotopic abundances are interpreted to reflect primary values as well. It was demonstrated for sample 353 that a fresh appearance cannot be considered absolute proof that the magmatic chemistry is preserved. Sample 353 may have undergone low temperature seawater alteration, only affecting its oxygen isotopic composition, K and volatile concentrations; alternatively, altered rock may have been incorporated into the magma prior to eruption of the lava. Thus, the alkalis, $\delta^{18}\text{O}$, $^{87}\text{Sr}/^{86}\text{Sr}$ and volatiles in the strongly fractionated and contaminated sample 353 will not be considered in the following discussion.

5.3 FRESHNESS OF THE WHOLE ROCK SAMPLES

On Figures 4.2 - 4.10 glass data show a smaller scatter of major and trace element concentrations than whole rock data. This can be an effect of secondary alteration. Petrographic descriptions of the samples already revealed that a large amount of secondary minerals replaced groundmass and phenocrysts (Table A.2).

To study the chemical changes during alteration, several corresponding glass - altered glass - whole rock samples were analyzed (Table A.17, A.18) for major elements, some trace elements and isotopic ratios. Samples without extensive alteration were used, so that the differences between glass and whole rock composition are minimum deviations. The degree of alteration will be discussed first for major elements and then for trace elements and isotopic compositions, and further in relation to rock type, primary chemical composition and stratigraphy.

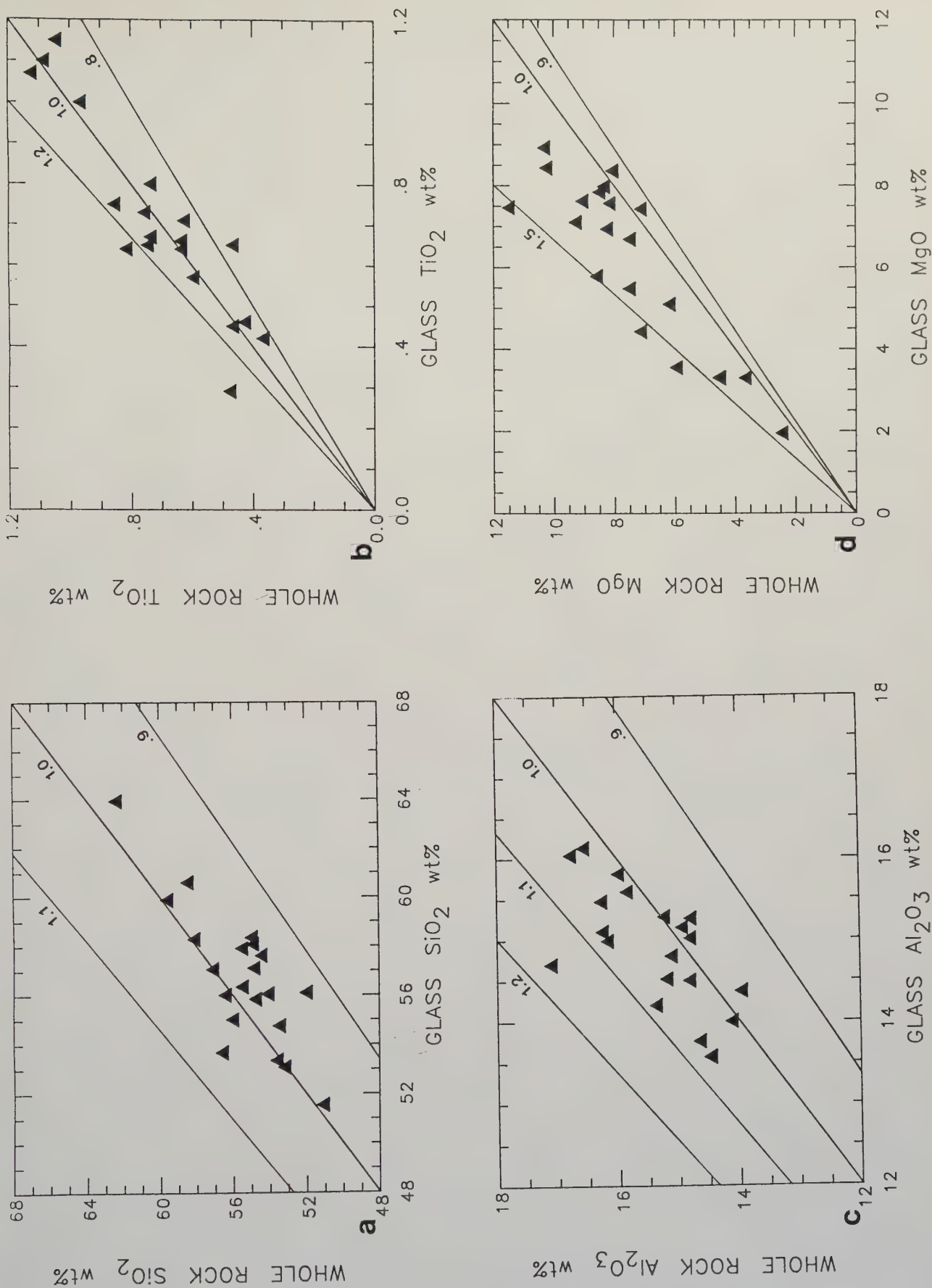
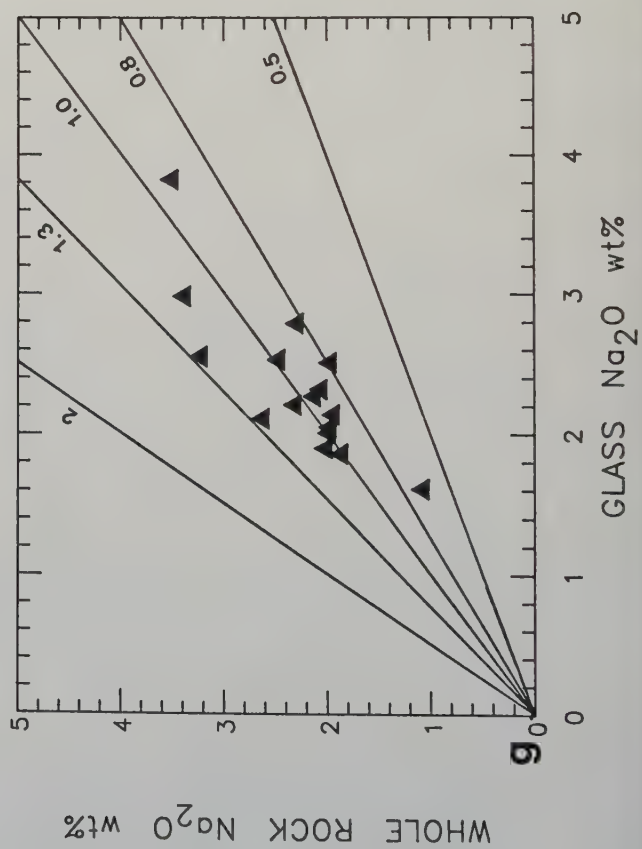
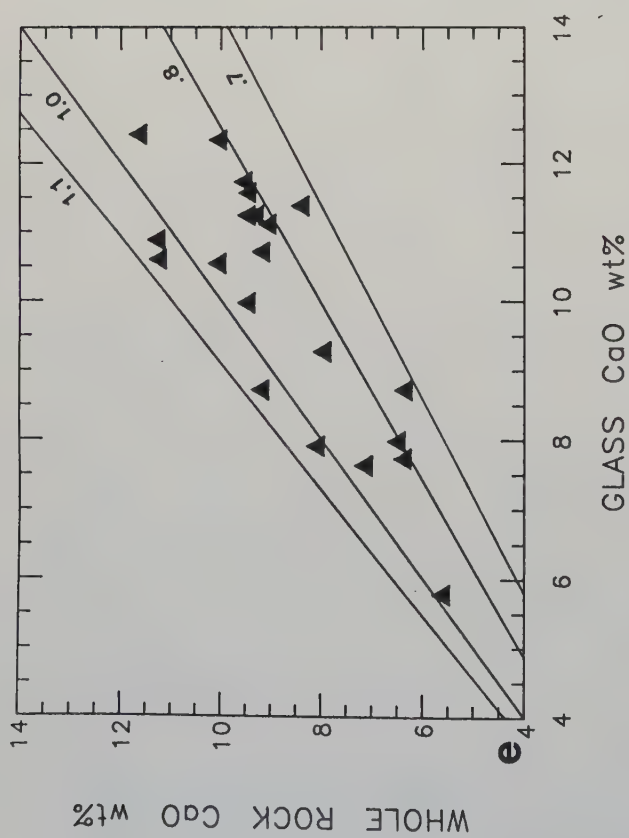
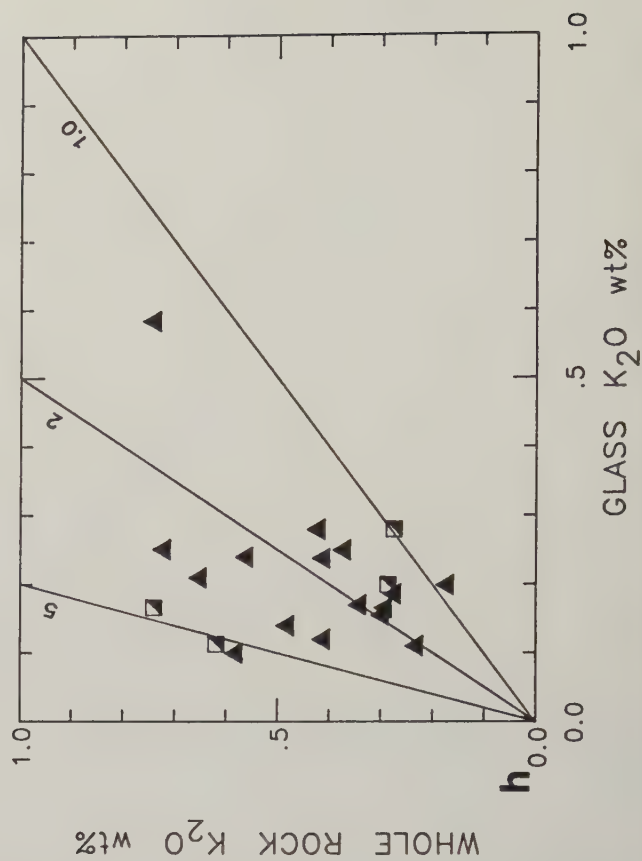
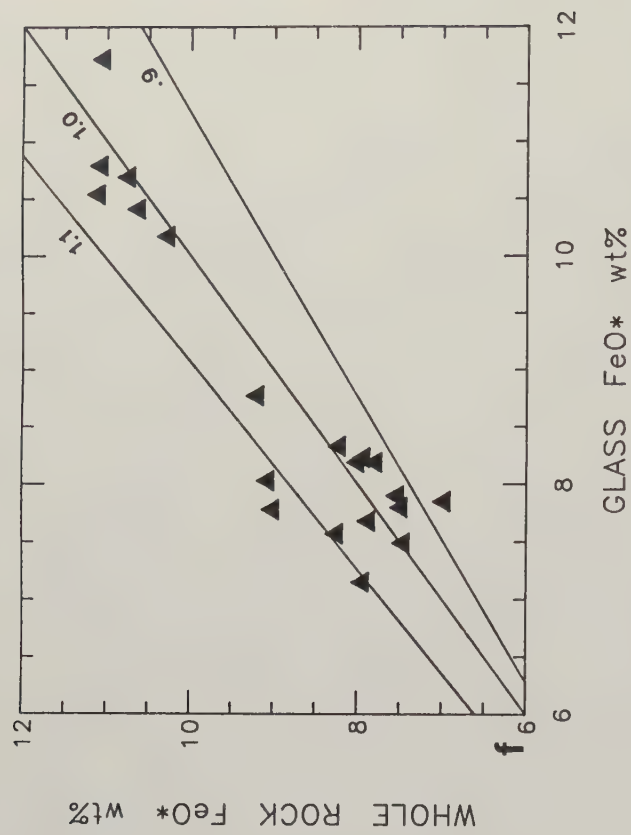
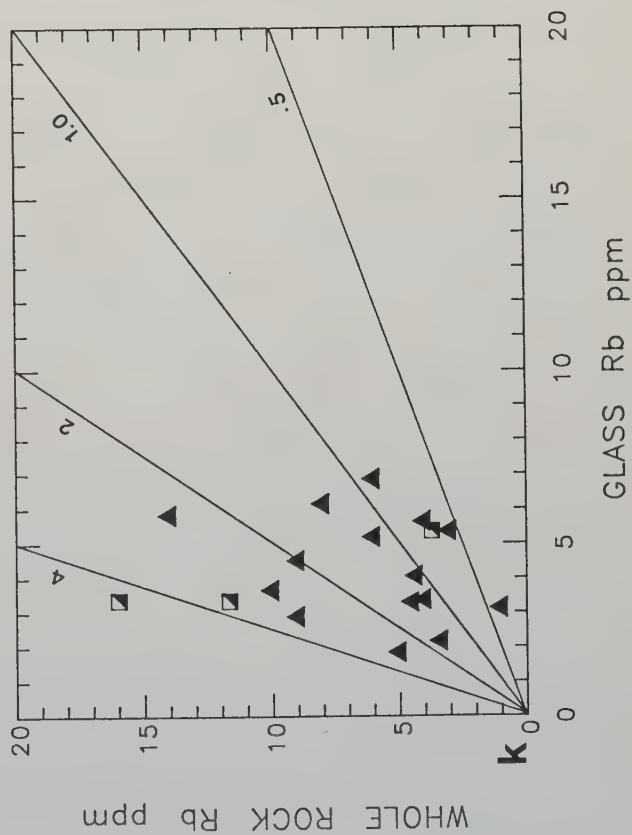
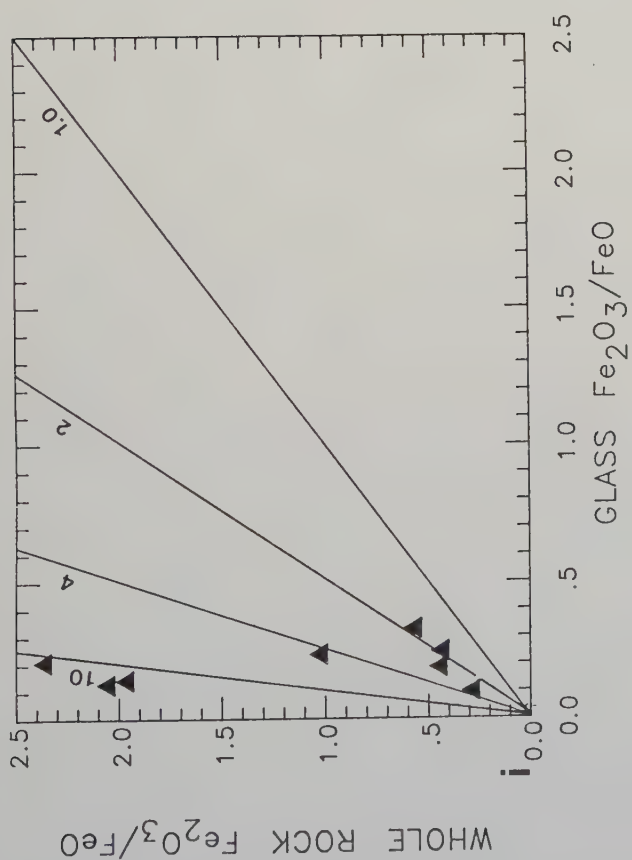
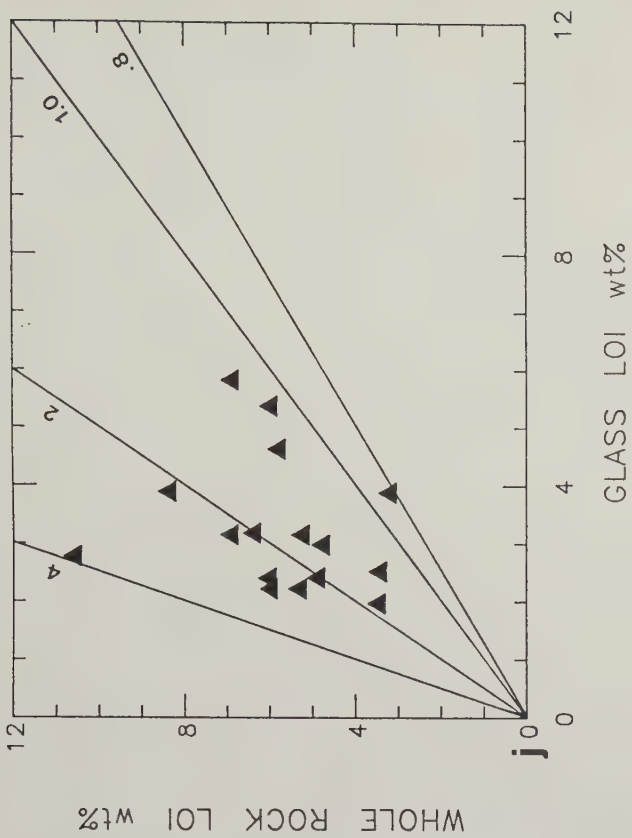


Fig. 5.4a-k. Concentrations of major and trace elements in glass separates and corresponding whole rocks. Corresponding altered glasses are half-filled squares. The lines indicate ratios of concentrations in whole rock/ concentration in glass.





5.3.1 MAJOR ELEMENTS

SiO_2 , TiO_2 , Al_2O_3 , FeO^* of the glasses are correlated with MgO with relatively little scatter, whereas the whole rock compositions show much more scatter (Fig. 4.2 - 4.5). Even larger are the differences between whole rocks and glasses for CaO , Na_2O , K_2O and loss on ignition. The contents of CaO , Na_2O , K_2O , and loss on ignition show correlations with MgO for the glasses, but most of the whole rock data plot towards lower CaO , lower and higher Na_2O , and higher K_2O , and loss on ignition (Fig. 4.6 - 4.8).

Figure 5.4 shows the concentrations of major elements in the glasses versus those in corresponding whole rocks. In most cases, SiO_2 contents in glasses are lower than in the whole rocks, corresponding to a loss of up to 10 %, mostly around 2 to 7 %. TiO_2 abundances in whole rocks and corresponding glasses are very similar, and no systematic difference in whole rocks is apparent compared with the glasses. Apart from two exceptions, the TiO_2 differences are less than 8%, the analytical error of the determination. Al_2O_3 concentrations are slightly higher in the whole rocks compared to the glasses, mostly between 5 to 8%. MgO contents are significantly (up to 60%) greater in whole rocks than in the corresponding glasses. This is due to decomposition of the glassy groundmass in the whole rocks and its replacement with Mg-rich clay minerals such as smectite. CaO contents of the whole rocks show are 10 to 30% lower than in the glasses. Fig 4.6 indicates that some of the analyzed severely altered rocks have probably lost more than 50 % of their original CaO content. FeO^* remains rather constant for glass and whole rock pairs. Only a few samples show random changes of up to 15%. In contrast, $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios range from 0.11 to 0.28 (with a mean of 0.18) in the glasses, but are drastically higher in the whole rocks, up to values of 2.5 suggesting that most whole rocks have been strongly oxidized by secondary alteration. Na_2O contents scatter in the whole rocks. K_2O contents (Fig. 4.8) of the fresh glasses show a restricted range whereas the data points for whole rocks and altered glasses plot towards much higher values. Altered glass samples have K_2O contents up to five times higher than the corresponding whole rocks. Severely altered whole rocks may contain up to 9 weight % K_2O (Fig. 4.8). Loss on ignition values, representing the total volatile content of the glasses, lie between 2 and 5.5 weight %, whereas whole rock loss on

ignition are up to three times greater.

5.3.2 TRACE ELEMENTS

Transition elements such as Sc, Co, Cr, V, and Ni were not measured on whole rock - glass pairs, thus a direct comparison is impossible. These elements are often referred to as insensitive to alteration (Condie et al., 1977, Pearce & Cann, 1973, Winchester & Floyd, 1977). The same holds true for the HFS elements Ta, Ti, Hf, Zr, Nb, and the REE elements due to their low concentrations in seawater (Hart et al., 1974, Condie et al., 1977, Pearce, 1983). For REE, this has been confirmed by analysis of a whole rock - glass pair (sample 340, Table A.17, Fig. 5.5).

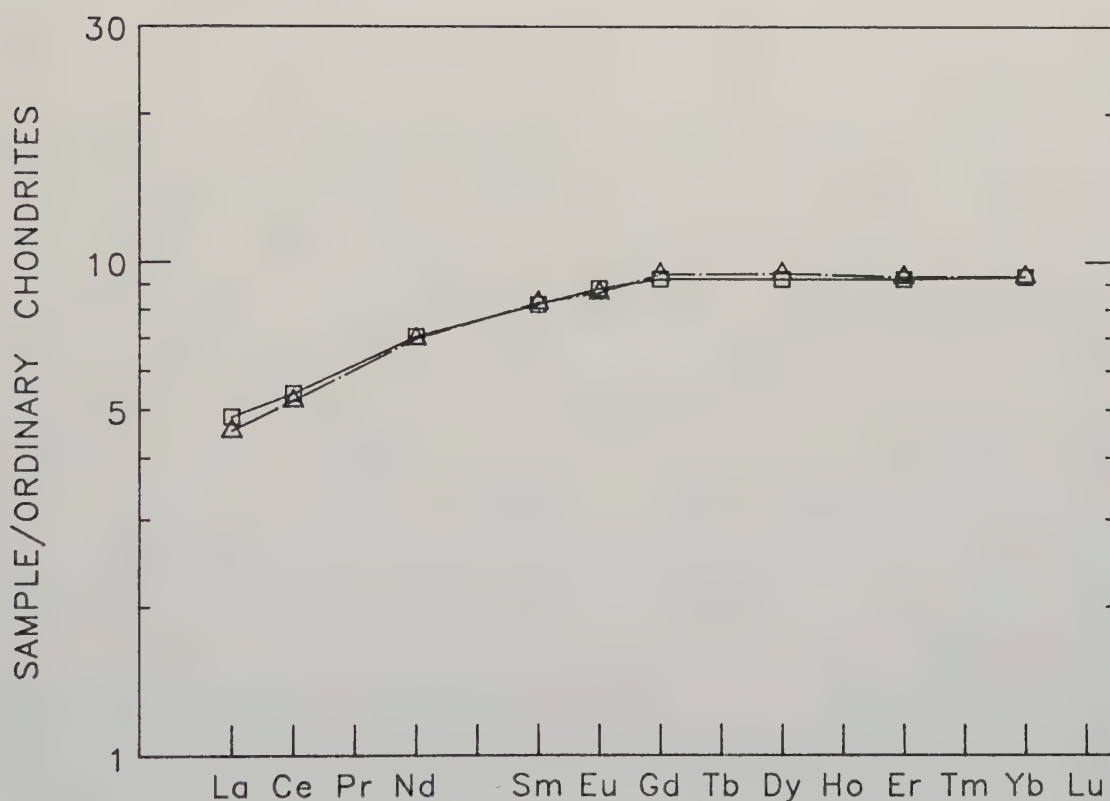


Fig. 5.5. REE concentrations (normalized to chondrites) in sample 340 for glass (triangles) and whole rock (squares).

In contrast, LFS elements (K, Rb, Cs, Sr, Ba) are sensitive to low temperature alteration (Hart, 1971; Staudigel et al, 1981a, 1981b, 1983). In Troodos whole rocks, Rb and K are greater than in the glasses (Fig.4.8, 4.16, 5.4k). Sr contents scatter towards lower or

higher values (30 to 100 % change) (Fig. 4.15, Table A.17). Cs contents are lower in altered glass and whole rocks (Table A.17). Ba contents scatter to lower or higher values in whole rocks and altered glasses (Fig. 4.14, Table A.17).

5.3.3 ISOTOPIC RATIOS

Nd and Pb isotopic compositions are assumed to be unaltered by seawater alteration, as the Nd and Pb concentrations in seawater are very low (DePaolo & Wasserburg, 1977, Faure, 1986, Patterson, 1971). In contrast, Sr and O isotopic compositions are increased by low temperature alteration (Hart, 1971; Staudigel et al., 1981a, 1981b, 1983). This is confirmed by the higher $^{87}\text{Sr}/^{86}\text{Sr}$ and $\delta^{18}\text{O}$ for altered glasses and whole rocks, a shift more pronounced for altered glass than for whole rocks (Fig. 5.1, Table A.18).

5.4 DISCUSSION

The Troodos whole rocks are mainly aphyric (Table A.2). Therefore the differences between whole rock and glass in the analyzed pairs are unlikely to be caused by phenocrysts in the whole rocks. In addition, the chemical differences between glasses and whole rocks, e.g. the higher K_2O , loss on ignition and $\text{Fe}_2\text{O}_3/\text{FeO}$ ratios, and the loss in CaO cannot be explained with a higher concentration of phenocrysts in the rocks. Instead, the observed chemical changes, namely the gain of MgO , Na_2O , K_2O and loss of CaO in the rocks are consistent with low temperature alteration (Thompson, 1983). They are consistent with experimental data obtained by seawater alteration of fresh basalts at temperatures of 70°C by Seyfried & Bischoff (1979).

Field evidence from the Akaki River section shows that different rock types, e.g. pillows or sheet flows (see Chapter 2) show different types of alteration, especially in the species of their secondary minerals. Vesicles in pillow lavas, large lava bodies and large lava tubes show the same alteration pattern, and are often filled with smectite, calcite, analcime, phillipsite, nathrolite, gmelinite, and chabazite (Gillis & Robinson, 1985). The alteration pattern in sheet flows differs from that found in pillow lavas. Vesicles are partly filled with smectite, calcite, green celadonite, clinoptilolite, mordenite, opal-c, opal-ct, chalcedony, and quartz (Gillis & Robinson, 1985). Secondary minerals in vesicles in dikes are zeolites, smectite,

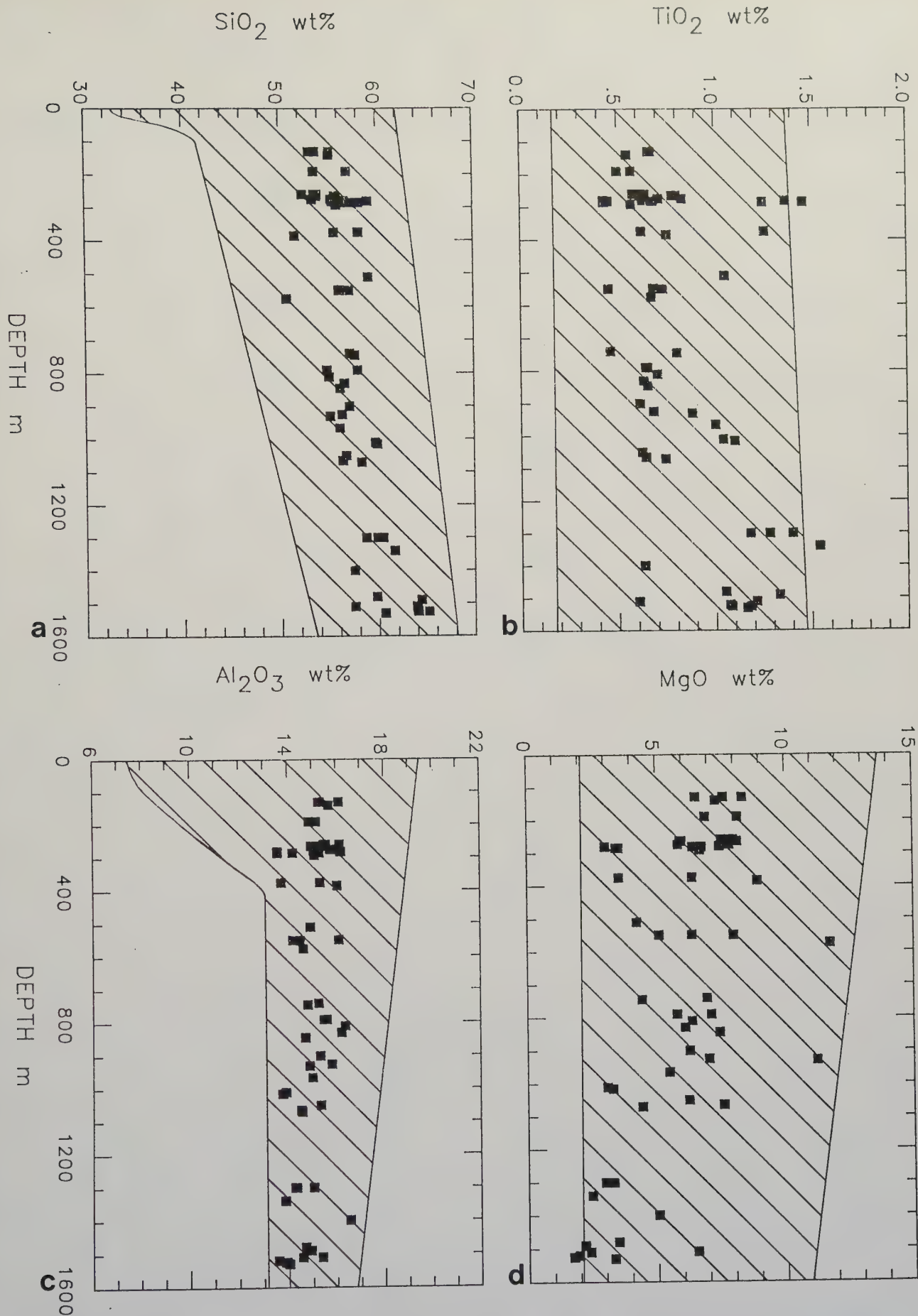
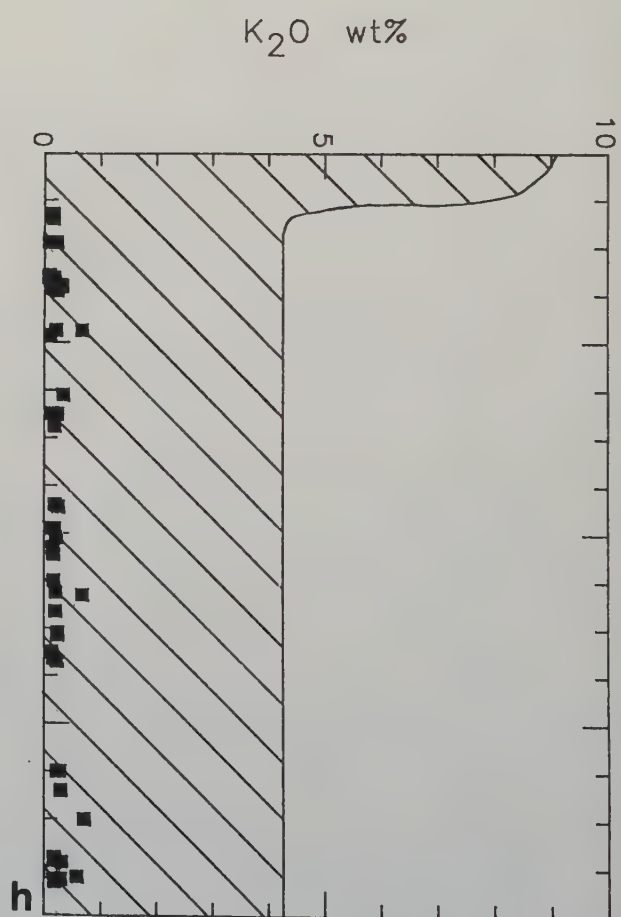
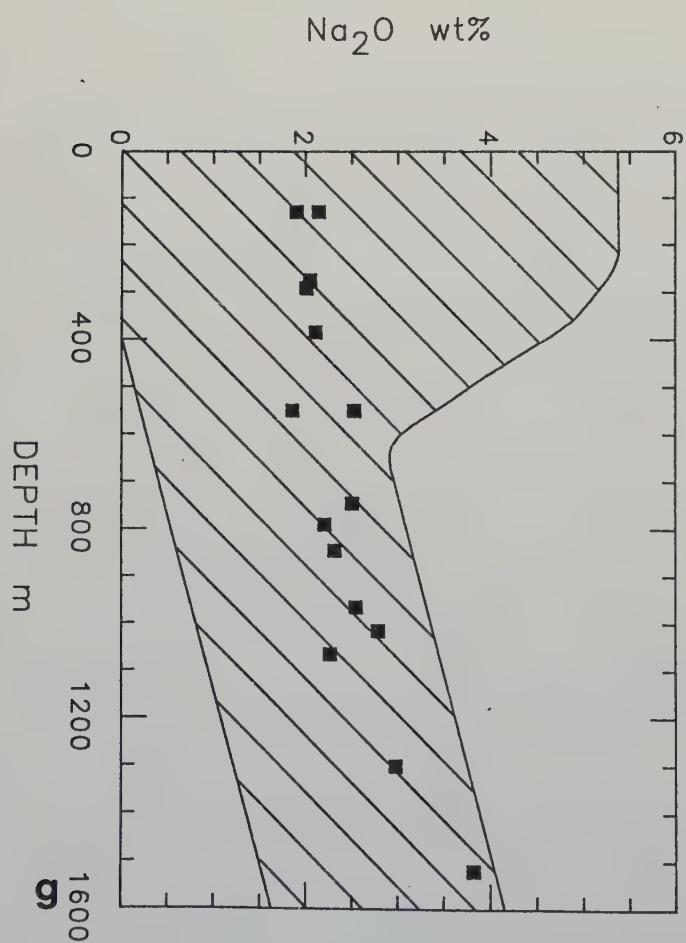
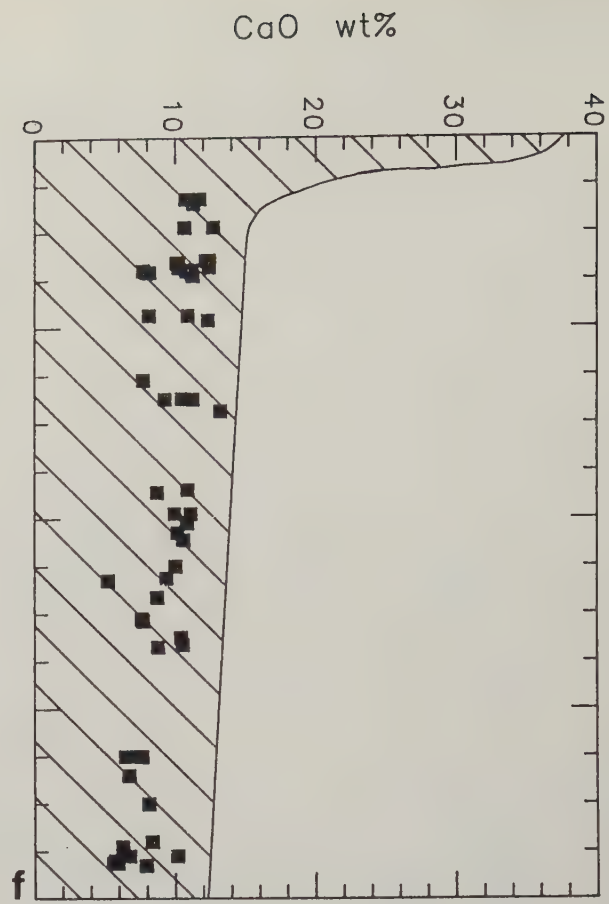
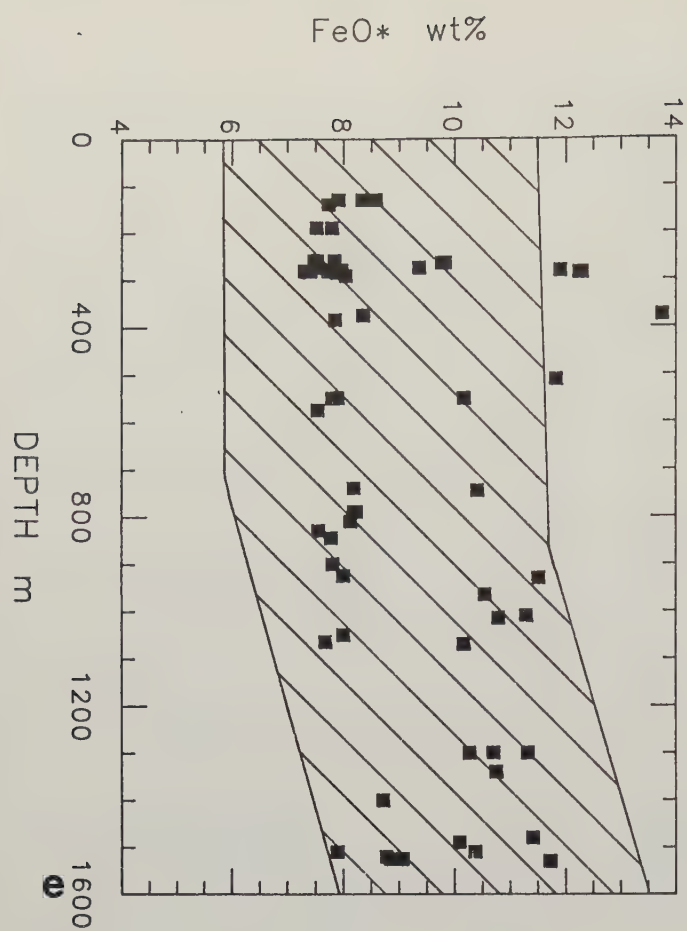
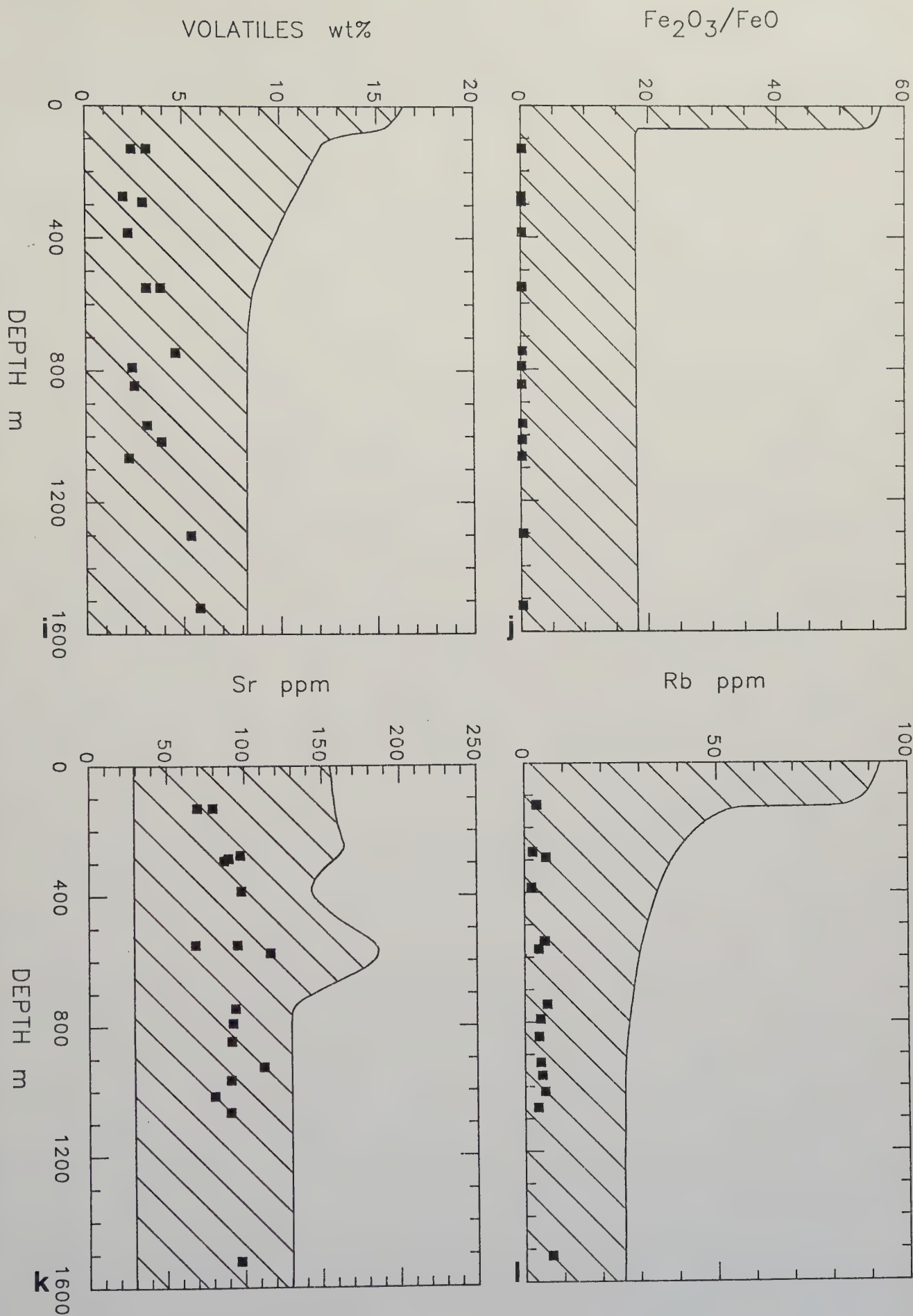


Fig. 5.6a-l. Concentrations in major and trace elements of all whole rocks (shaded areas) and all glasses (squares) versus stratigraphic depth. Note the larger spread of compositions of whole rocks in the upper level of the section.





chalcedony and quartz. However, no systematic differences in the chemical changes during alteration are apparent for different rock types considering the analyzed glass - whole rock pairs.

The chemical changes caused by alteration are also independent of the primary chemistry of the samples, because no systematic differences in the style of alteration are found between basaltic andesites and more differentiated volcanics.

Figures 5.6a-1 show the chemical composition of all analyzed samples plotted versus stratigraphic depth. There are systematic changes in the degree of alteration with stratigraphic depth in the sequence from the topmost unit A to the lowermost unit L. The systematic changes described for the whole rock - glass pairs, namely the loss of CaO, and Na₂O, and the gain in MgO, K₂O and volatiles is confirmed for most of the whole rock samples throughout the stratigraphy (Fig. 5.6a-1). At the top of the section, the degree of alteration is higher. The strongly altered whole rocks in the upper few hundred meters part of the section show large losses in SiO₂ and Al₂O₃, high Fe₂O₃/FeO ratios and strong enrichments in CaO, Na₂O, K₂O, volatiles, Sr, Rb, and Ba. TiO₂ and FeO* contents show no systematic changes with stratigraphic depth. These changes are due to the extensive alteration of the uppermost lavas, during which all olivine phenocrysts in the olivine rich lavas were replaced by calcite, and the groundmass was altered to smectite and zeolites. In addition, the lavas underwent extreme oxidation, resulting in an increase in Fe₂O₃/FeO ratios.

These findings are consistent with those in the low temperature alteration zone in the drill core of CY 2a from the Cyprus Drilling Project (Sunkel et al., submitted). In summary, the whole rocks in the upper part of the section are more extensively altered than those from deeper stratigraphic levels. This is consistent with findings in modern ocean floor basalts. Volcanic rocks from the surface of the present-day seafloor are more pervasively altered, and have high Fe₂O₃/FeO ratios and high volatile contents, whereas the rocks from deeper crustal levels are often less altered. At these levels, fresh glass is present and the rocks are less oxidized (Thompson, 1983). This suggests that the uppermost lavas in the Akaki Canyon represent

the sea floor at the time of deposition and erosion of the volcanics before deposition of the overlying sediments is not significant.

5.5 CONCLUSIONS

All glass compositions are considered to be fresh for major and trace elements contents and Sr, Nd, Pb, and O compositions, with the possible exception of glass sample 353, which will not be discussed in the following chapters.

Even the comparably little altered whole rocks chosen for comparison with the glasses are significantly altered in some major elements (MgO, CaO, Na₂O, K₂O, and LOI). The LFS elements (K, Rb, Cs, Sr, Ba) in the whole rocks are completely altered. Altered glasses show a larger change in concentrations of these elements than whole rocks. Only immobile trace elements such as Sc, Cr, Co, V, Ni, HFS elements and REE of whole rocks are considered to represent the primary composition. Nd isotopic compositions of the whole rocks can be regarded as primary values, whereas Sr and O isotopic ratios are higher than in the glasses.

The chemical changes in altered glasses and whole rocks are characteristic for low temperature seawater alteration. The volcanics of the upper stratigraphic levels in the Akaki River section are more extensively altered than the lower levels. This is consistent with alteration patterns in modern ocean floor volcanics.

The results demonstrate that the alkali contents of even moderately altered samples have increased to such an extent that chemical classifications based on the abundances of Na and K in such rocks can be completely meaningless.

CHAPTER 6. CHEMICAL RELATIONSHIPS WITHIN THE EXTRUSIVE SERIES

6.1 INTRODUCTION

The chemical compositions of the Akaki River volcanics range from basaltic andesites through andesites to dacites. This chapter will address the question whether the chemical composition of these volcanics is correlated with the stratigraphy, and whether they are derived from a common magma source or from several sources. A more detailed treatment of their magma genesis will be given in Chapter 8.

Field work in the Akaki River section led to the concept of distinct stratigraphic volcanic units erupted in a relatively short time intervals with following short gaps in the volcanic activity (see chapter 2). The relationship between the volcanic model deduced from the field evidence and the chemical composition of the volcanics will be examined.

Several subdivisions of the Troodos extrusive series into two stratigraphic units, Upper and Lower Pillow Lavas have been proposed earlier, based on field observations (Wilson, 1959, Bear, 1960, Gass, 1960, Gass & Smewing, 1973). Later studies had suggested a stratigraphic and chemical division into a lower andesite-rhyodacite series and an overlying more mafic series (Robinson et al., 1983, Schmincke et al., 1983). An attempt will be made to clarify whether divisions based on chemical characteristics can be confirmed by this study and whether these groups are related to the stratigraphy.

6.2 CHEMICAL COMPOSITION AND STRATIGRAPHY

In the Akaki River section the stratigraphic position and the relative age of the volcanics is known accurately only for the extrusive rocks. The relative ages of the intrusive rocks are less well constrained, only a minimum age can be determined, i.e. younger than the extrusive host rock and older than time of termination of overall volcanic activity. Therefore only the extrusives in the Akaki River section will be considered for an evaluation of the relationship between chemical composition and stratigraphy. The intrusive rocks and their chemical relationship to the extrusives will be considered afterwards.

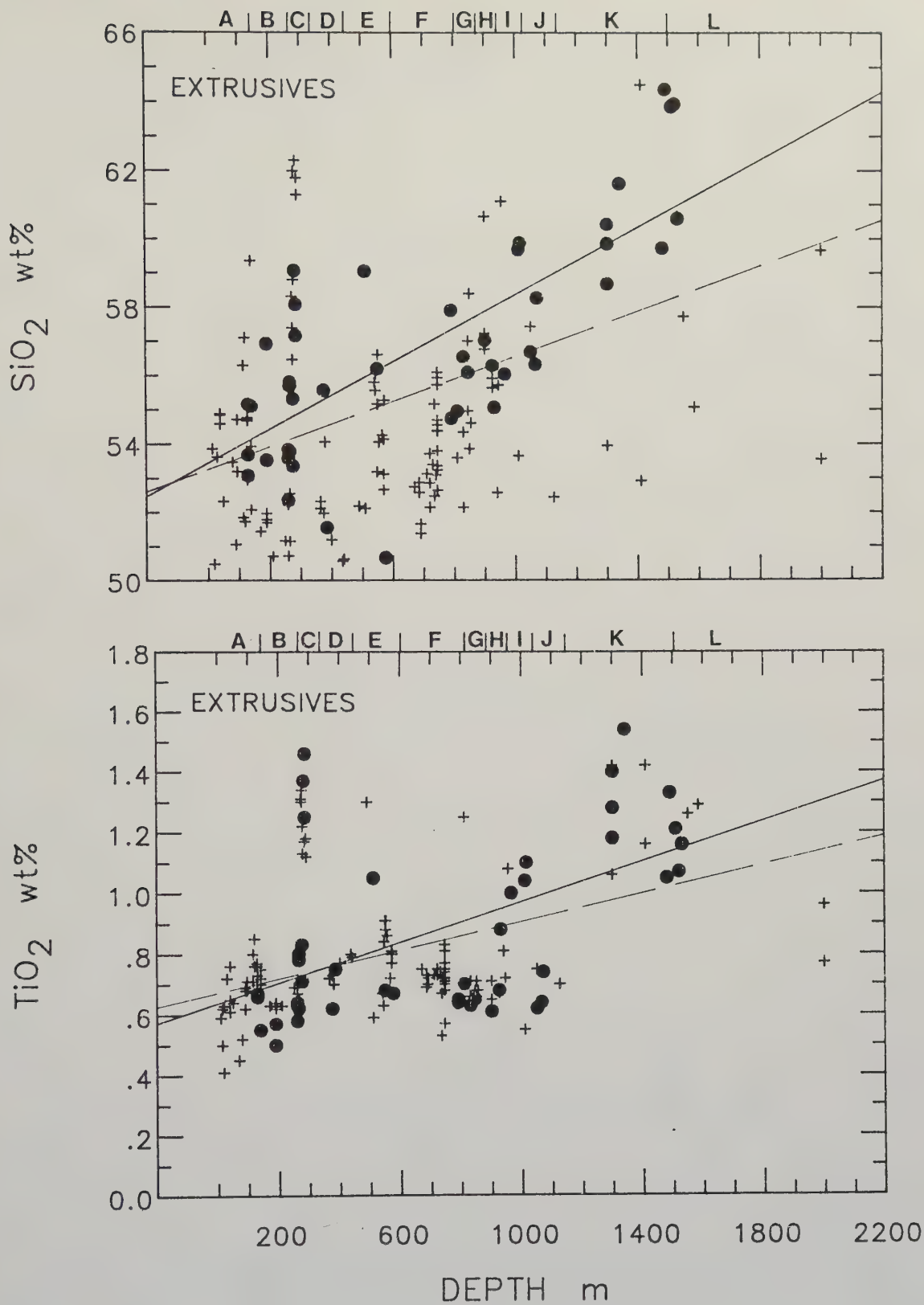


Fig. 6.1. SiO_2 and TiO_2 versus stratigraphic depth for extrusives (dots = glasses, crosses = whole rocks). Intervals of stratigraphic units are marked. Regression lines are shown for glasses (solid) and glasses plus whole rocks (dashed).

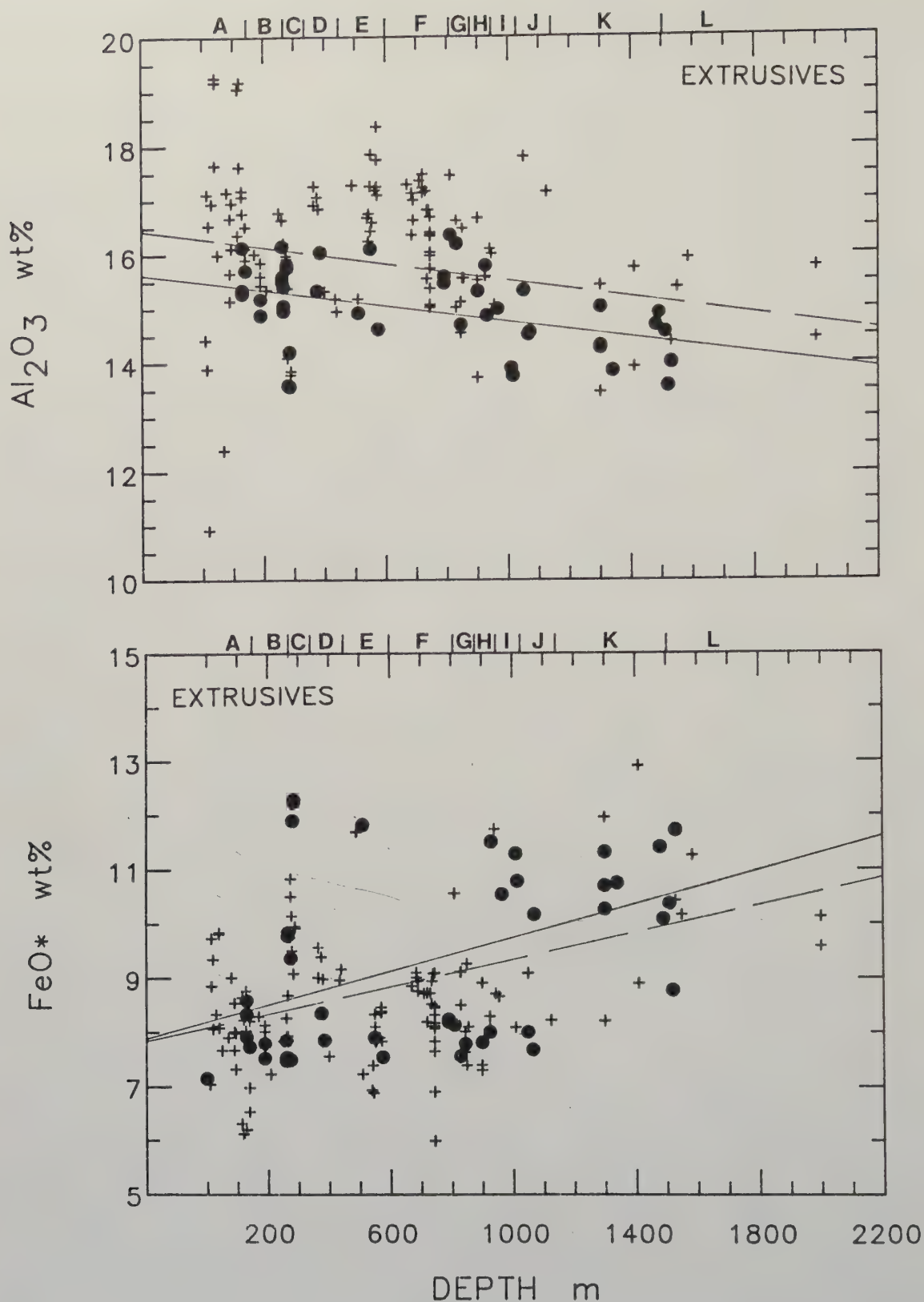


Fig. 6.2. Al_2O_3 and FeO^* versus stratigraphic depth for extrusives (dots = glasses, crosses = whole rocks). Intervals of stratigraphic units are marked. Regression lines are shown for glasses (solid) and glasses plus whole rocks (dashed).

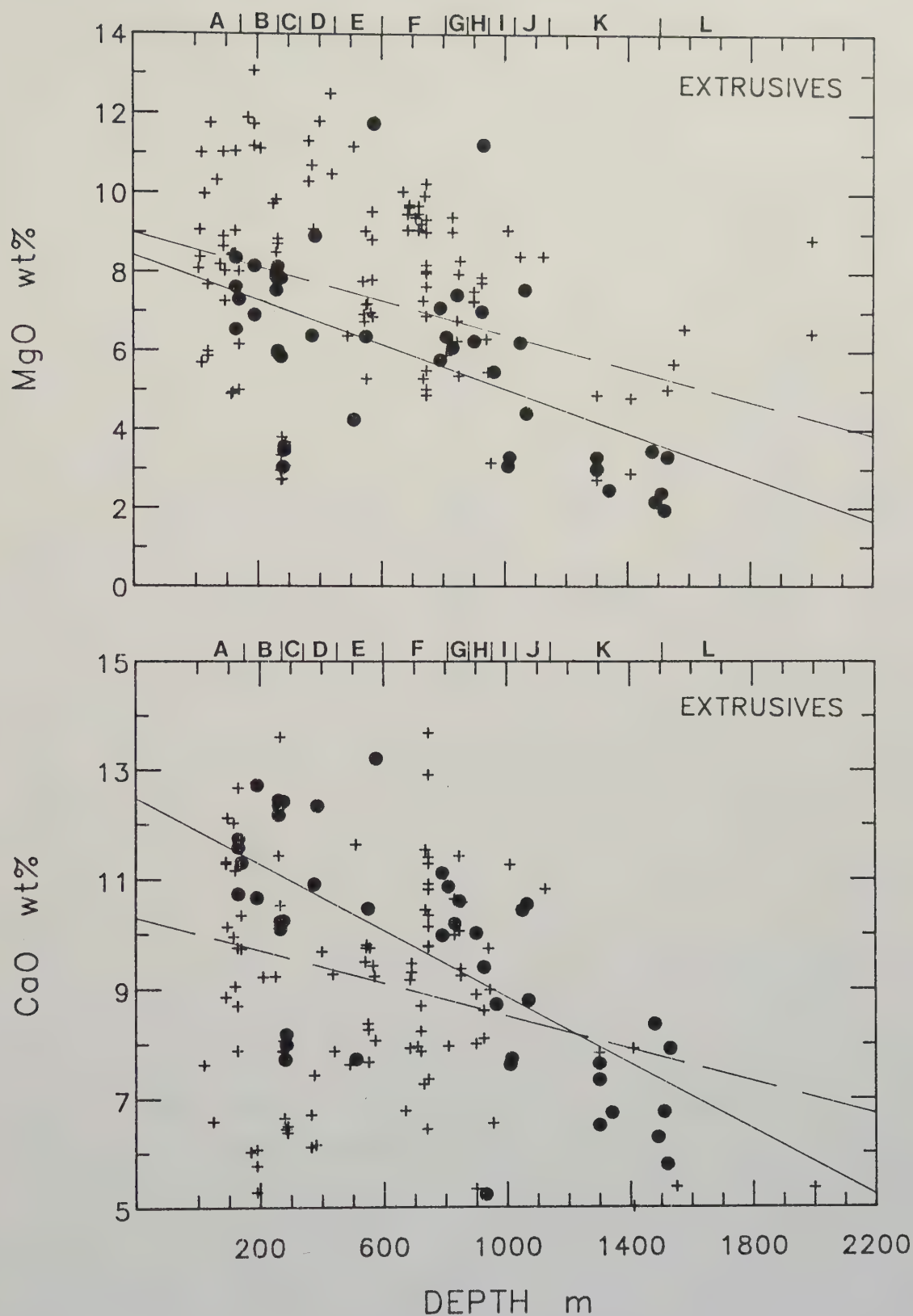


Fig. 6.3. MgO and CaO versus stratigraphic depth for extrusives (dots = glasses, crosses = whole rocks). Intervals of stratigraphic units are marked. Regression lines are shown for glasses (solid) and glasses plus whole rocks (dashed).

Table 6.1. Correlations between stratigraphic depth and major element concentration (Akaki River).

		A	B	r	n
SiO ₂	glasses	53.20	.0051	.76	46
	glasses +	53.14	.0033	.46	157
	whole rocks				
TiO ₂	glasses	.64	.0003	.53	46
	glasses +	.67	.0002	.43	165
	whole rocks				
Al ₂ O ₃	glasses	15.53	-.0007	-.46	46
	glasses +	16.27	-.0008	-.27	164
	whole rocks				
FeO*	glasses	8.17	.0015	.44	47
	glasses +	8.03	.0012	.40	166
	whole rocks				
MgO	glasses	7.87	-.0028	-.58	46
	glasses +	8.53	-.0021	-.38	165
	whole rocks				
CaO	glasses	11.85	-.0031	-.70	46
	glasses +	10.12	-.0015	-.31	147
	whole rocks				
Ti/Zr	glasses	136	-.0110	-.20	16
	glasses +	129	-.0060	-.13	133
	whole rocks				

$Y=A+Bx$ is the equation of the regression line, r the correlation coefficient, and n the number of samples.

6.2.1 MAJOR ELEMENTS

SiO₂ contents of the extrusive glasses show a broad trend towards higher SiO₂ with increasing stratigraphic depth in the section (Fig. 6.1). For whole rocks the general trend is less pronounced. TiO₂, Al₂O₃ and FeO* contents of the glasses and whole rocks show a less pronounced, but nevertheless systematic trend with increasing stratigraphic depth (Fig. 6.1, 6.2). However, high and low TiO₂, Al₂O₃ and FeO* occur in the lower and upper part of the section. Within individual stratigraphic units there is a significant variation of these elements, e.g. TiO₂ in stratigraphic units C, F, and L. MgO contents and Mg# of glass samples show a trend towards lower MgO with stratigraphic depth. However, mafic and differentiated compositions are present at each stratigraphic level. MgO of whole rocks show a similar variation. Many whole rocks have higher MgO contents, but in most cases due to alteration, (see chapter 5), and/or to olivine

phenocrysts in cumulates. (Fig. 6.3). CaO contents in the glasses show a broad correlation towards decreasing CaO with increasing depth (Fig. 6.3). Many whole rocks, especially of the upper part of the section, show low CaO contents, due to alteration (see chapter 5). Na₂O and K₂O of the glass samples show a slight trend towards increasing values with increasing depth. Whole rocks are too altered to give any constraints for these elements.

There is a general trend from more differentiated, silica-rich volcanics at the base of the section to more mafic volcanics at the top. Correlation coefficients for major element compositions and stratigraphic depth for glasses only and for glasses plus whole rocks are given in Table 6.1. The correlation coefficients for glasses range from 0.44 to 0.76, and -0.46 to -0.70. Coefficients for glasses plus whole rocks are generally smaller.

6.2.2 TRACE ELEMENTS

In Fig. 6.4, Ti/Zr ratios are plotted versus stratigraphic depth. Ti/Zr ratios vary between 70 and 180 and no systematic trend with depth can be observed. In mafic volcanics, Ti/Zr ratios are not changed by fractional crystallization, and give an indication of the homogeneity of the magma source. However, in highly differentiated volcanics with low MgO contents Ti may be fractionated by crystallization of magnetite and ilmenite, so that the Ti/Zr ratio decreases. Fig. 6.5 shows MgO versus Ti/Zr ratios of glass samples. The variation in Ti/Zr ratio is large, independent of the degree of differentiation of the samples, and the full variation in Ti/Zr ratios is present in mafic compositions, where oxide fractionation plays no role. Thus the observed variation of Ti/Zr ratios at high MgO contents is considered to be a feature of the magma source (Fig. 6.5). The Ti/Zr ratio varies significantly in units A, B, E, F, G, I, K, and L (Fig. 6.6), whereas it is almost constant in the other units. The Ti/Zr ratios of the differentiated extrusives of units K and L may not represent their magma source, because they may have been changed by fractionation of an oxide phase. Ba/Rb ratios in mafic volcanics are unlikely to be influenced by fractional crystallization, because this ratio is only affected by crystallization of K-feldspar or large amounts of plagioclase. No K-feldspar is observed in the Troodos volcanics, and plagioclase fractional crystallization probably does not play a major role for

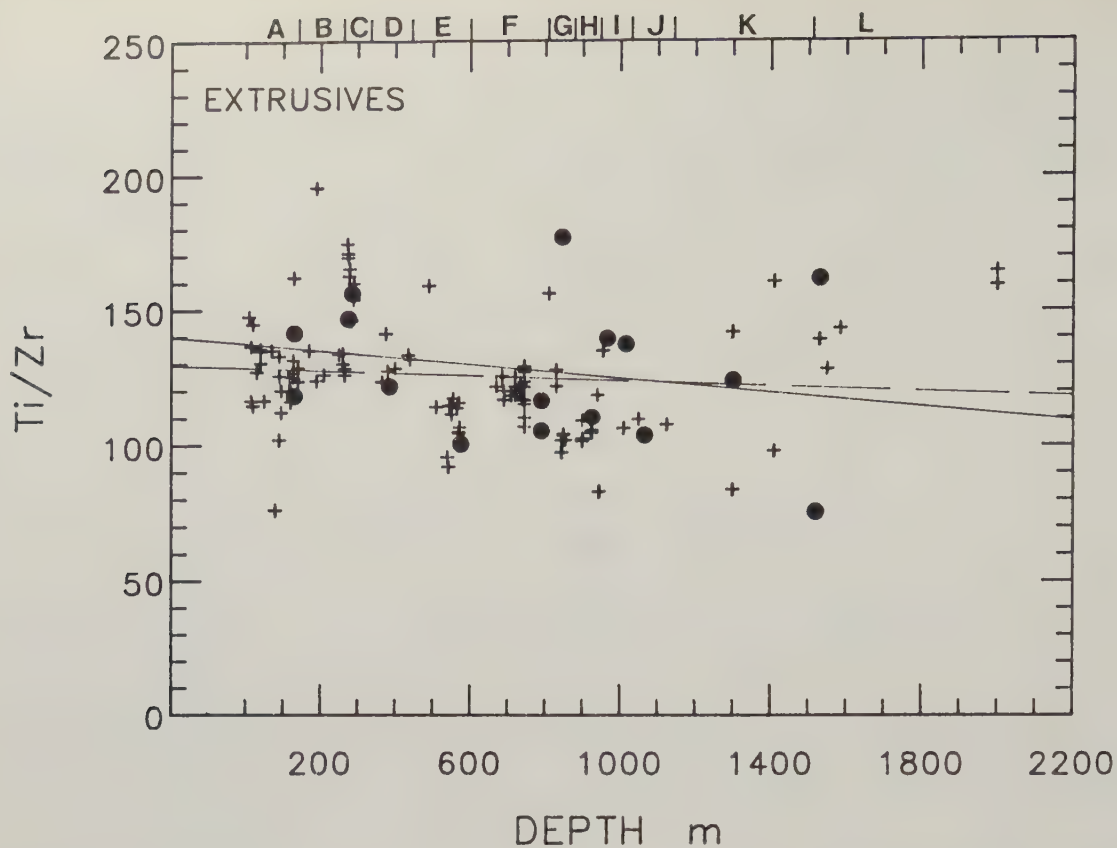


Fig. 6.4. Ti/Zr ratios versus stratigraphic depth for extrusives (dots = glasses, crosses = whole rocks). Intervals of stratigraphic units are marked. Regression lines are shown for glasses (solid) and glasses plus whole rocks (dashed).

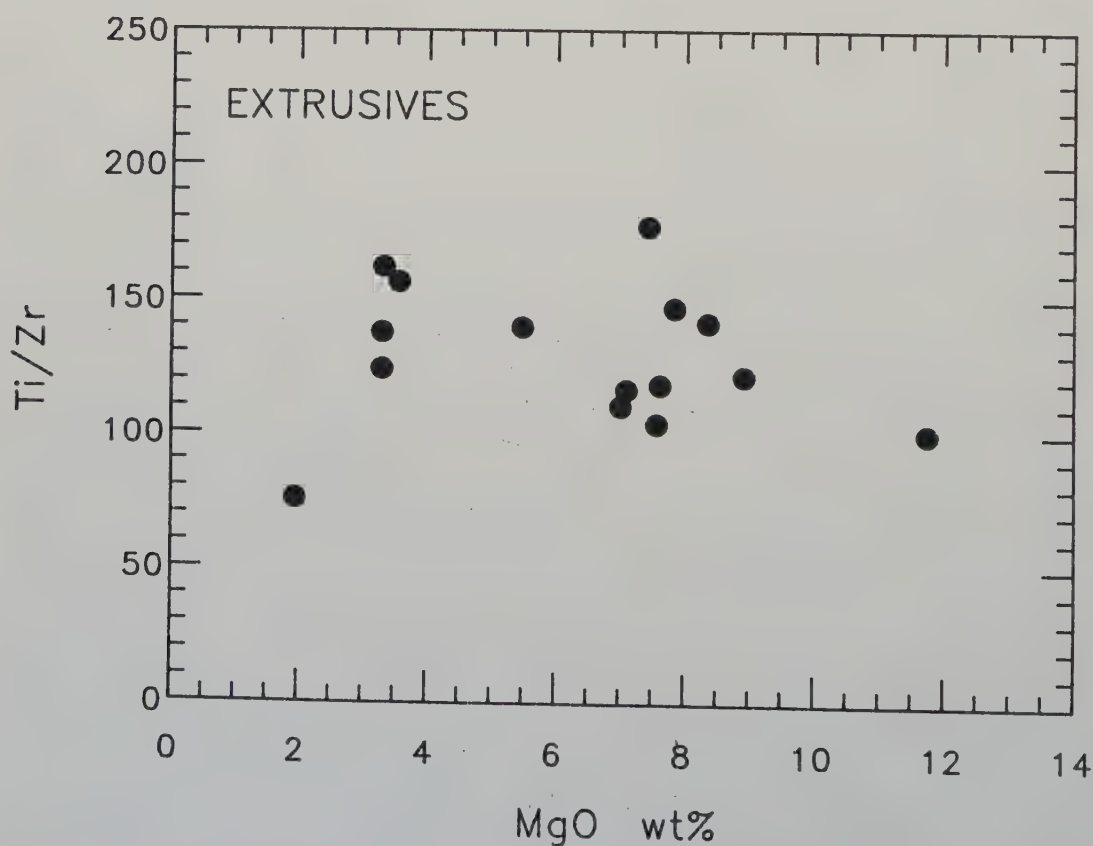


Fig. 6.5. MgO versus Ti/Zr ratios for glasses (dots).

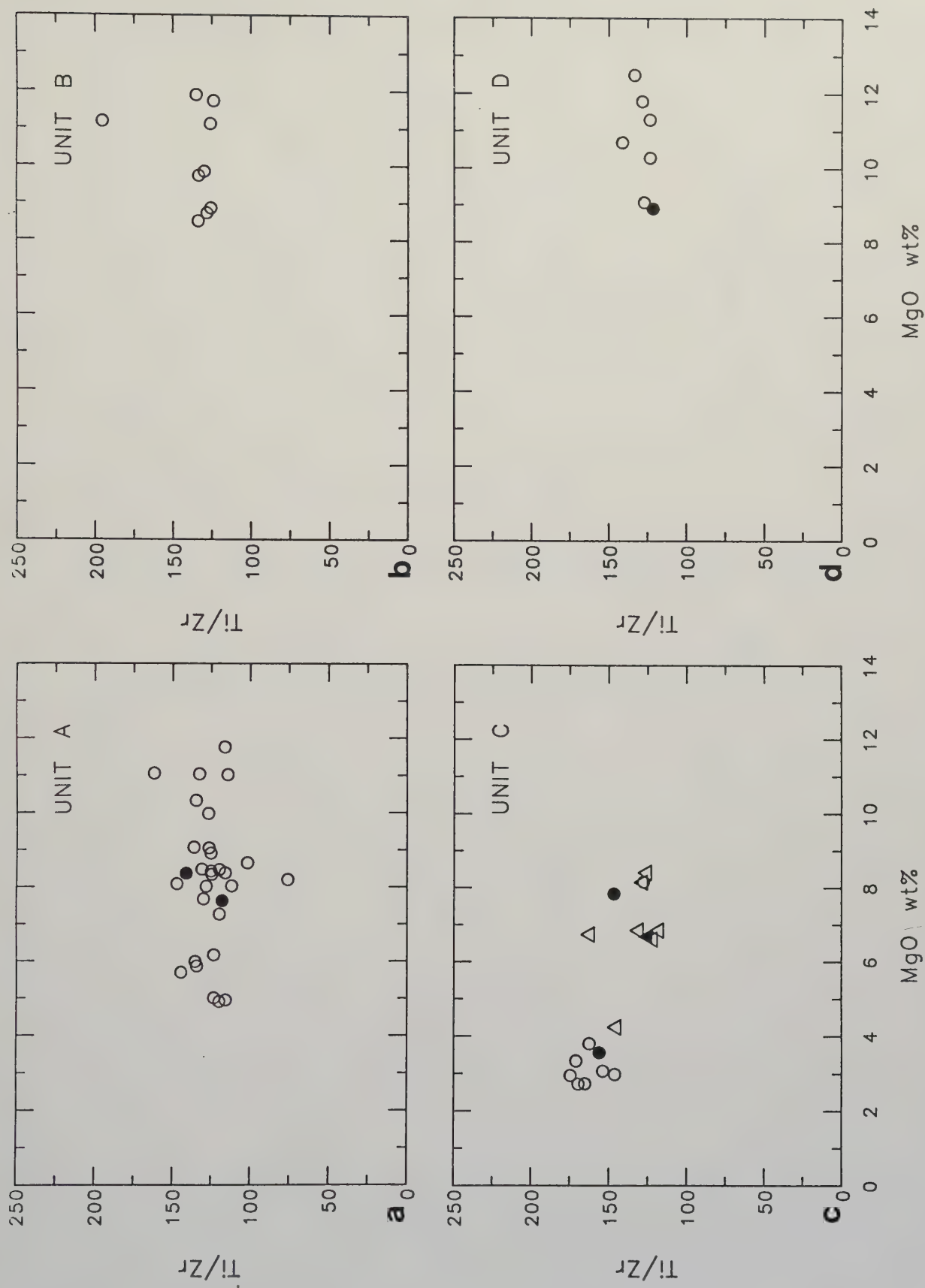
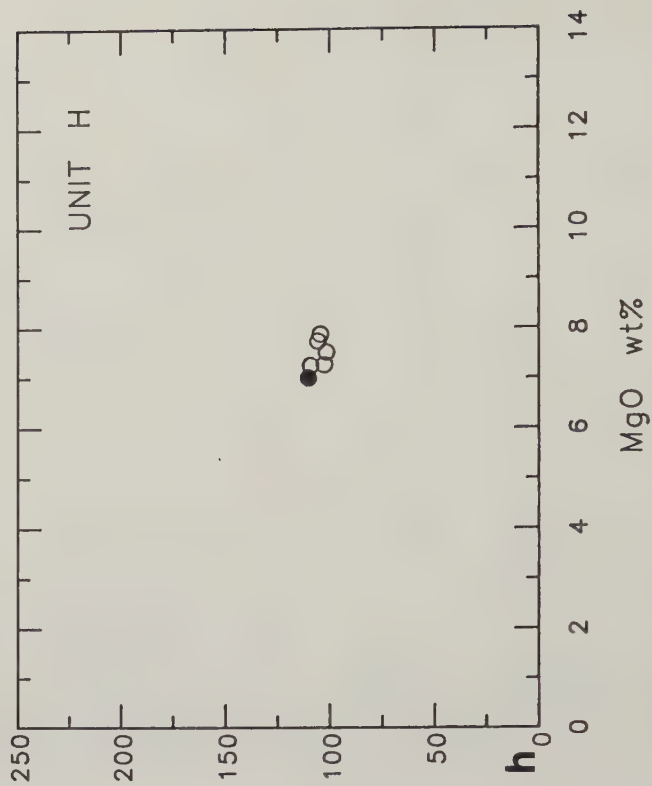
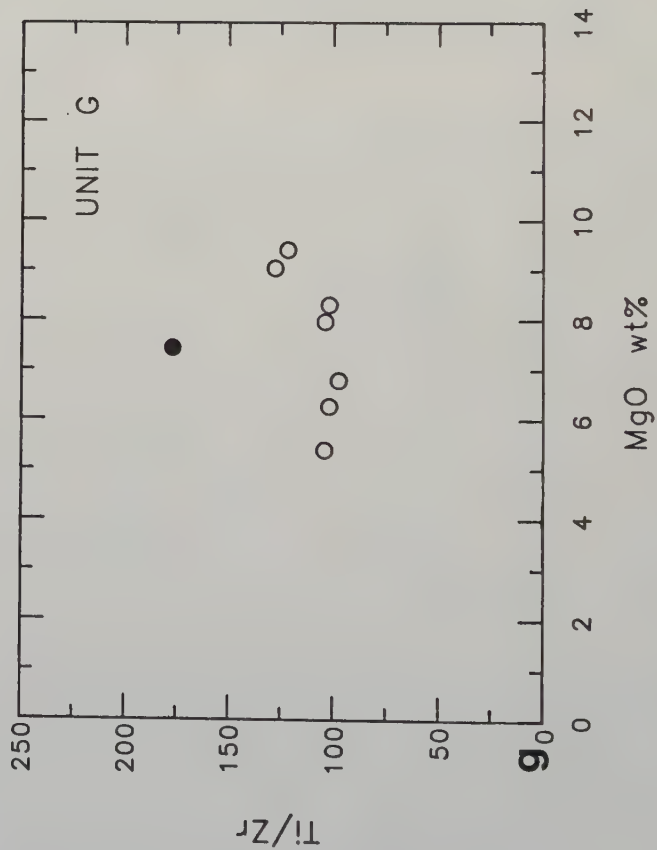
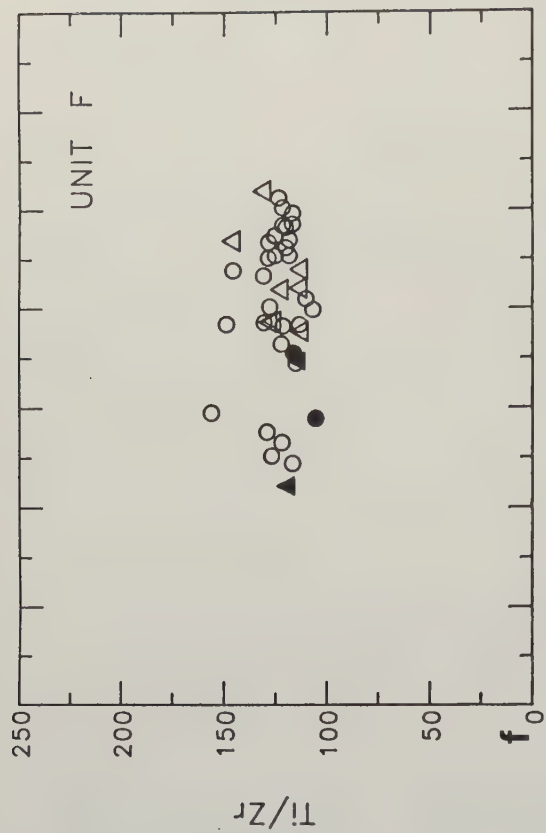
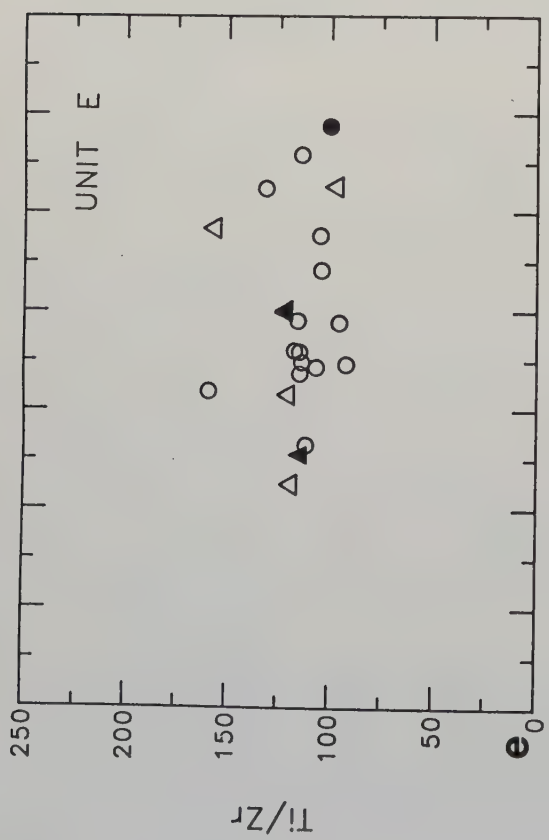
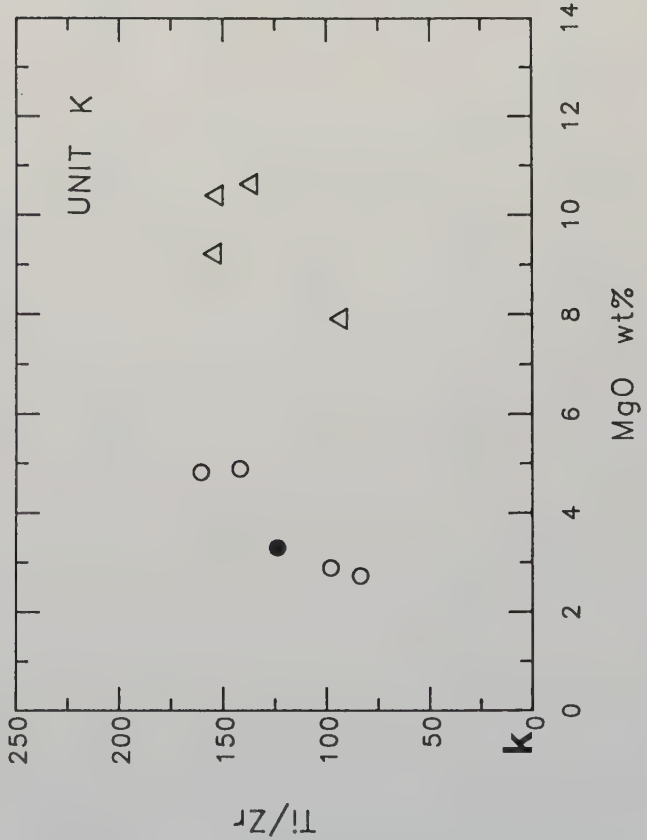
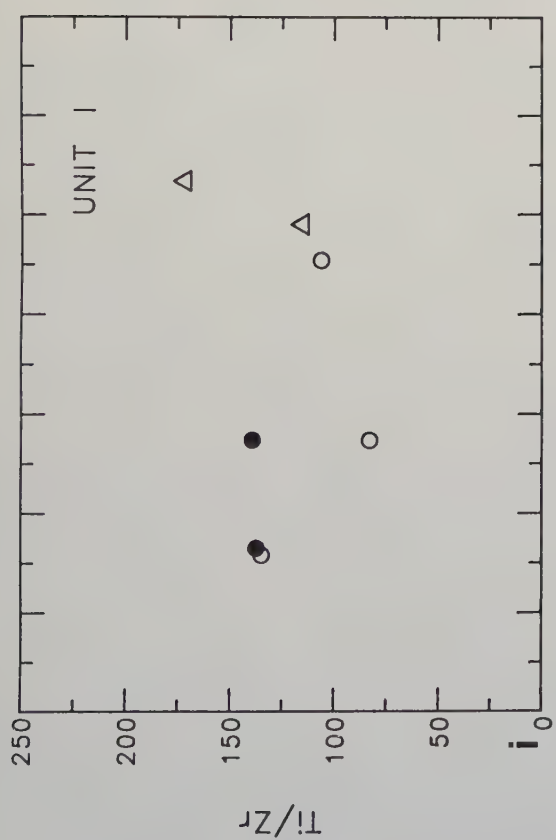
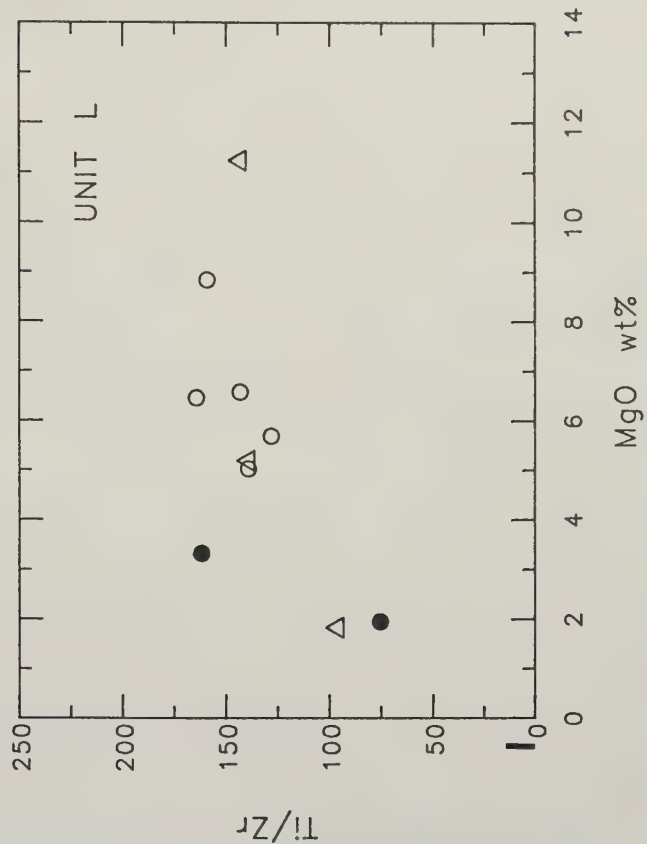
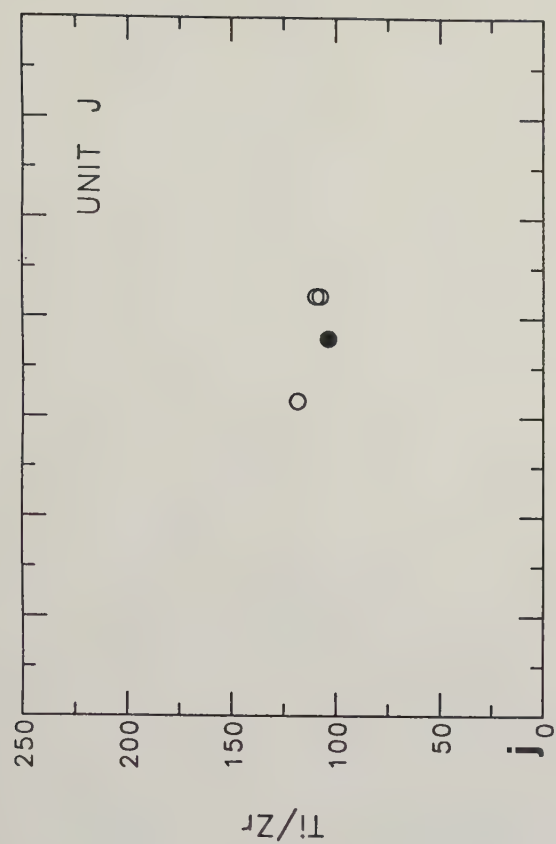


Fig. 6.6. Ti/Zr ratios versus MgO for individual stratigraphic units. Extrusives (dots = glasses, whole rocks = circles) and intrusives (solid triangles = glasses, open triangles = whole rocks).





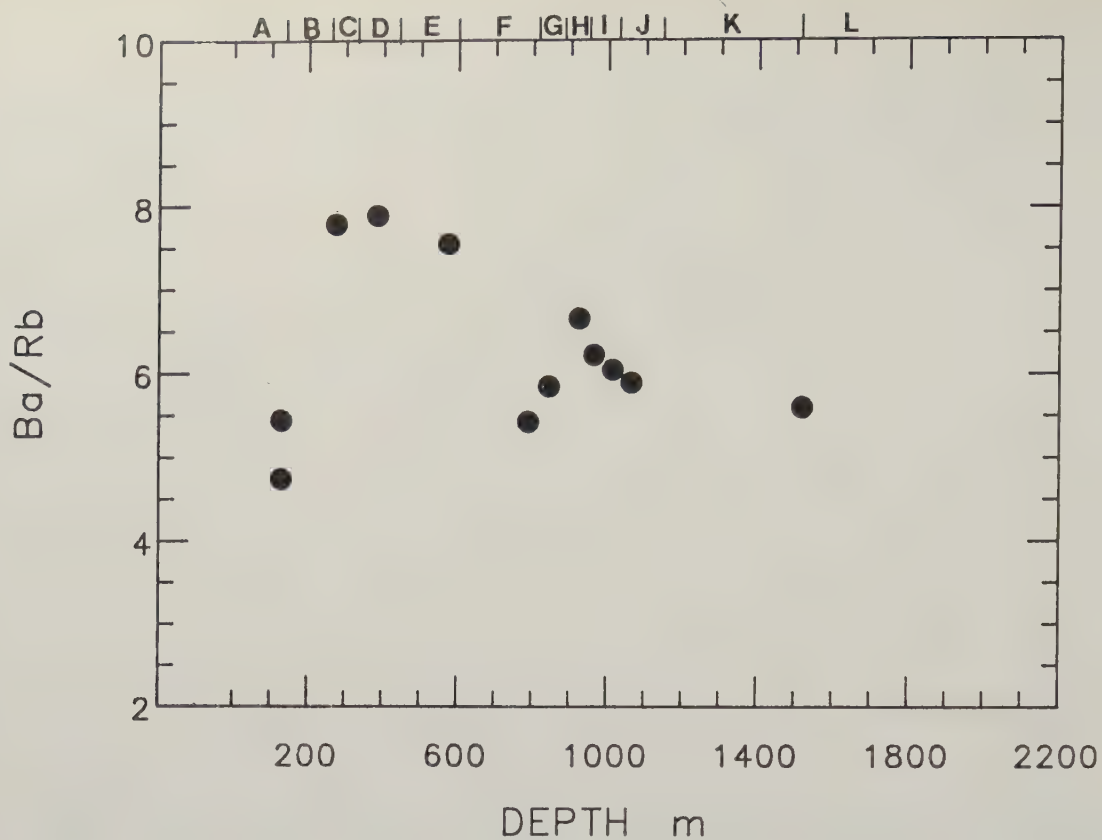


Fig. 6.7. Ba/Rb ratios versus stratigraphic depth for extrusive glasses (dots). Intervals of stratigraphic units are marked.

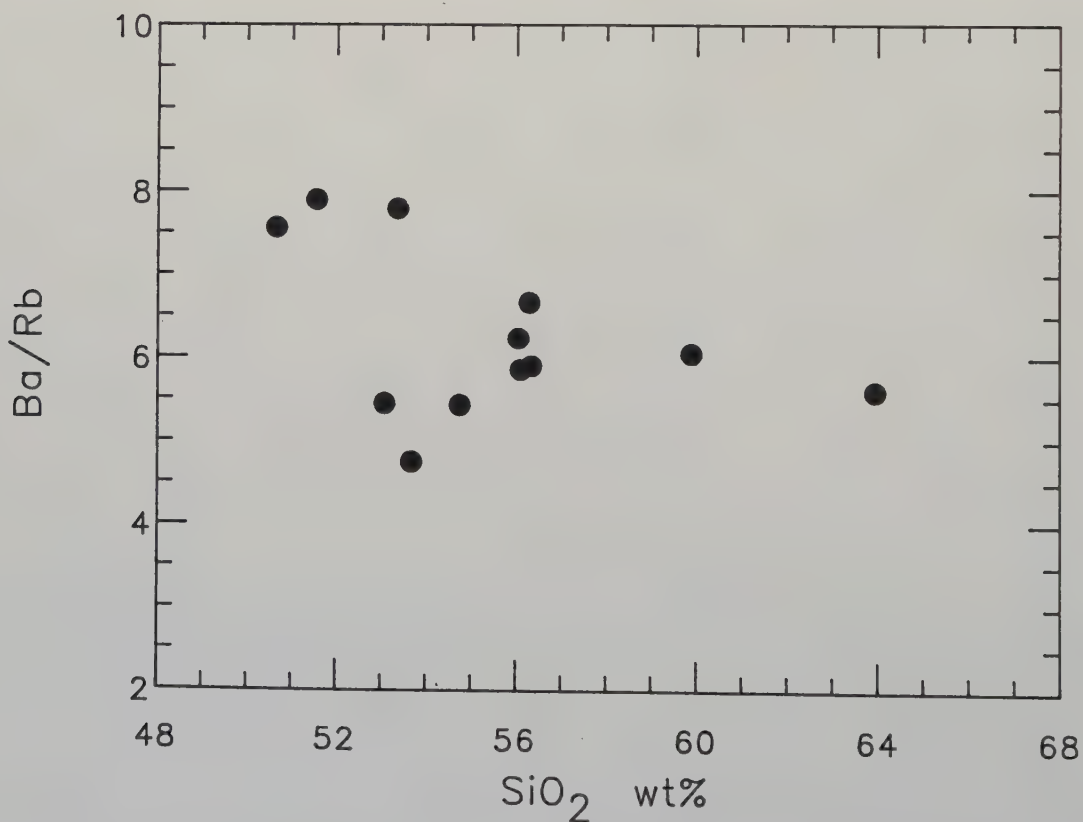


Fig. 6.8. Ba/Rb ratios versus SiO₂ for extrusive glasses (dots).

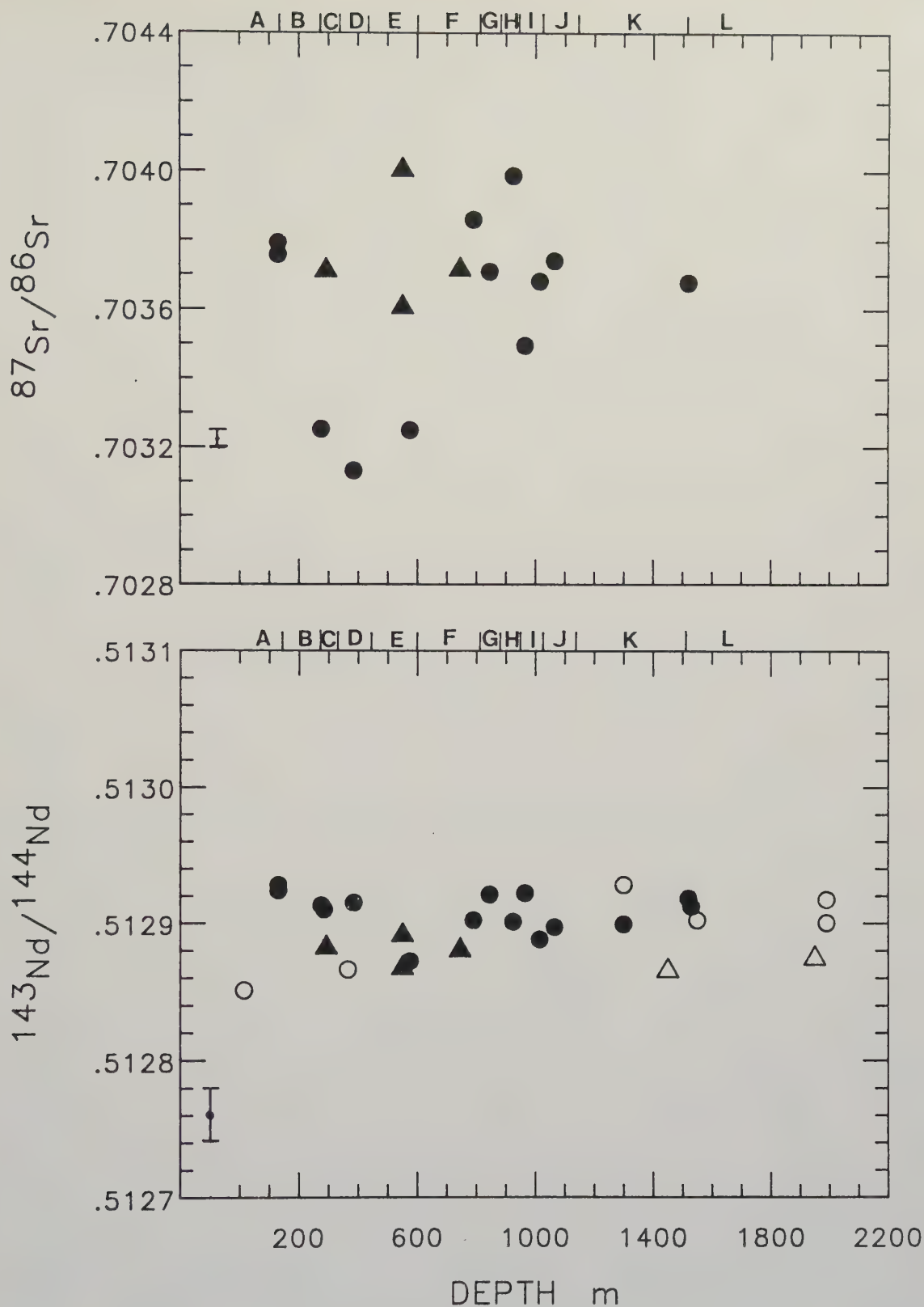


Fig. 6.9. $\text{Sr}^{87}/\text{Sr}^{86}$ and $\text{Nd}^{143}/\text{Nd}^{144}$ initial ratios versus depth for extrusives (dots = glasses, circles = whole rocks), and intrusives (solid triangles = glasses, open triangles = whole rocks). Intervals for stratigraphic units are marked. Error bar is shown.

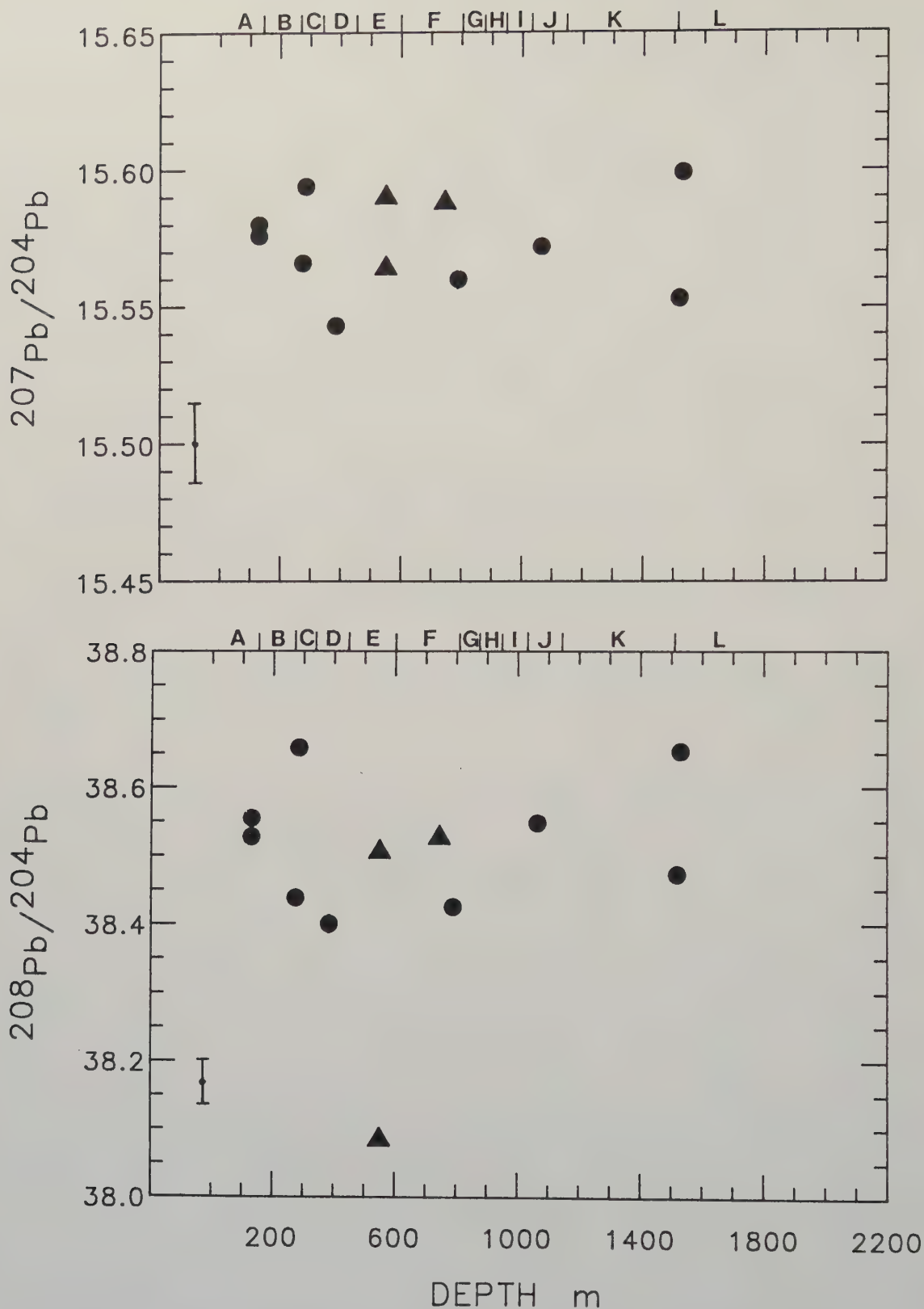


Fig. 6.10. Pb isotopic ratios versus depth for extrusive glasses (dots), and intrusive glasses (solid triangles). Intervals for stratigraphic units are marked. Error bar is shown.

mafic compositions. This is supported by the absence of a negative Eu-anomaly in the REE-patterns of the glasses. Therefore the Ba/Rb ratios of mafic Troodos glasses are thought to be similar to those of the magma source. Ba/Rb ratios in mafic glasses range from 3.8 to 7.9, and show no correlation with stratigraphic depth (Fig. 6.7, 6.8). This indicates that the magmas within the section, and also within individual stratigraphic units are heterogeneous in incompatible trace element compositions.

6.2.3 ISOTOPIC COMPOSITION

There are significant differences in Sr and Pb isotopic compositions for extrusive glasses, and less pronounced differences for Nd isotopic compositions of glasses and whole rocks, not only throughout the entire section but also within individual stratigraphic units. (Fig. 6.9 - 6.10). For none of the isotopic systems is there a correlation with stratigraphy. This confirms source heterogeneity, not only for the entire section, but also for individual stratigraphic units.

6.2.4 RELATIONSHIP BETWEEN VOLCANOLOGIC MODEL AND CHEMICAL COMPOSITION

In this study, the extrusive series was subdivided into twelve stratigraphic units on the basis of field criteria (see chapter 2). It was proposed that one, or several of these units combined, represent extrusive cycles that erupted in a relatively short time span, followed by a sharp break in volcanic activity. It will now be tested if this subdivision is also reflected in the chemistry of the volcanics.

Within the stratigraphic units, the major elements correlate with MgO in the same manner as they do for the entire extrusive series, but comprise a more restricted range of MgO contents (Fig. 6.11). Incompatible trace element ratios can be constant or variable within individual stratigraphic units (Fig. 6.6, 6.7). For example, Ti/Zr ratios can be considered homogeneous for units B, C, D, H, and J, whereas extrusives of units A, B, E, F, G, and I show a variation in Ti/Zr ratios, and therefore indicate a heterogeneity in the source. The Ti/Zr ratios of the differentiated extrusives of units K and L may not represent their magma source, because they may have been changed by

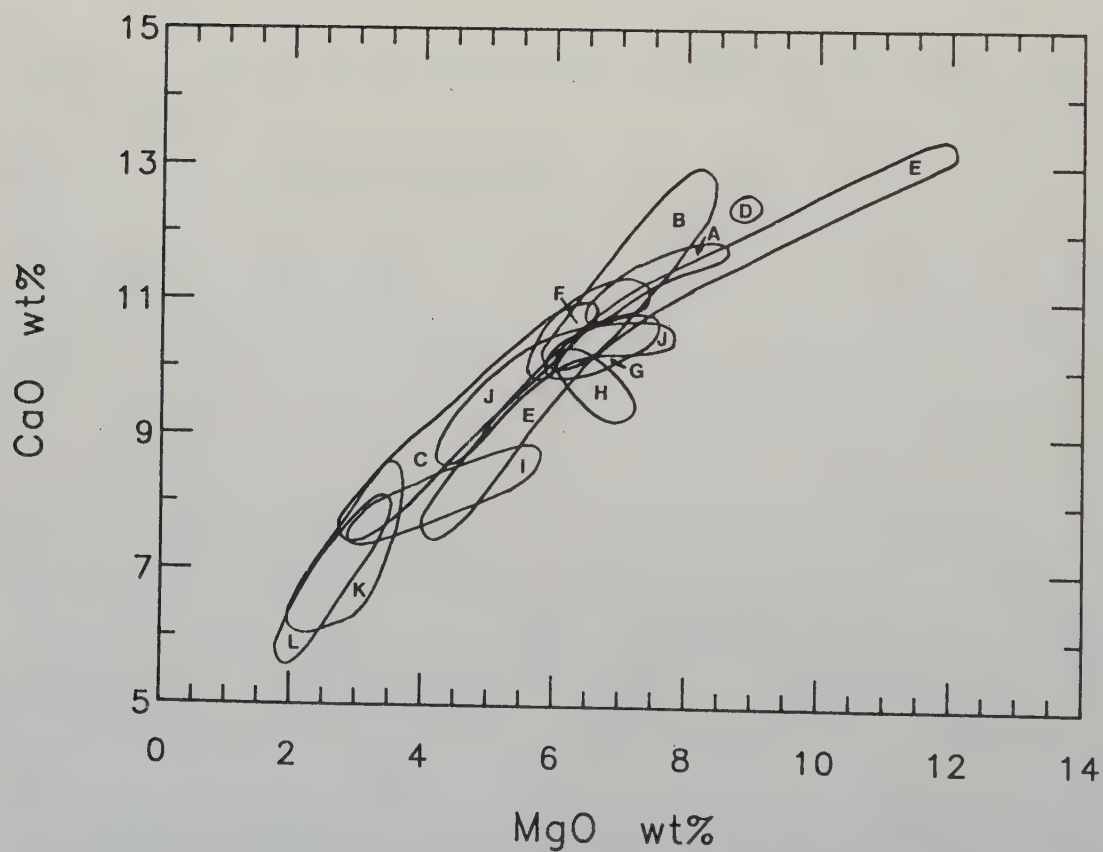
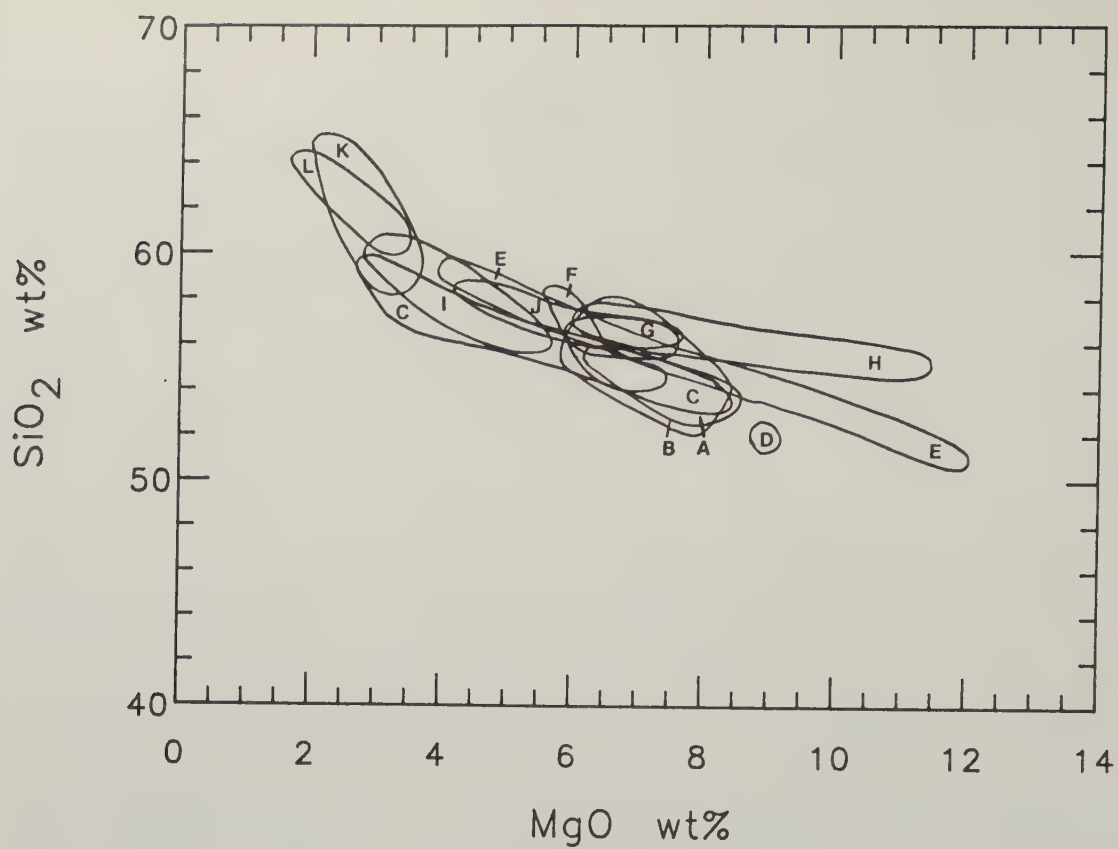


Fig. 6.11. SiO₂ and CaO versus MgO for extrusives. Fields of glass compositions are shown for individual stratigraphic units.

fractionation of an oxide phase. Ba/Rb ratios are not uniform within individual stratigraphic units, but the small data base limits the interpretation of this trace element ratio (Fig. 6.7). Isotopic ratios are different within and between individual units (Fig. 6.9 - 6.10), this also supports source heterogeneity within individual stratigraphic units. Furthermore, there is no systematic correlation between chemical composition and stratigraphic depth for the extrusive rocks within individual stratigraphic units.

In chapter 2, the formation of one or several stratigraphic units in one extrusive cycle was proposed, e.g. the units E-D and K-J were combined into one extrusive cycle. Major element compositions are in agreement with a formation of one or two stratigraphic units from one homogeneous magma, but Ti/Zr and Ba/Rb ratios and isotopic compositions are not consistent with this hypothesis. In fact, the individual units are heterogeneous in trace element and isotopic compositions.

In summary, there is evidence that the extrusives of individual stratigraphic units, and the stratigraphic units combined to extrusive cycles were formed by chemically heterogeneous batches of magma. There is, however, strong evidence that the lavas of the extrusive series were erupted in extrusive cycles (see chapter 2). This suggests that the processes causing heterogeneity of the magma are independent from the volcanic processes leading to the eruption of the stratigraphic units in extrusive cycles. A possible explanation may be the replenishment of a magma chamber with similar magmas having variable trace element and isotopic characteristics. If the magmas in the chamber did not mix thoroughly prior to eruption, several batches of magma from different sources could be tapped, even within the eruption of a unit. Thus, the model deduced for the volcanology remains valid, but it does not show a clear relationship to the chemical composition of the volcanics.

A general evolution of the major element chemical composition of the volcanics from differentiated to more mafic compositions is apparent from the glass data, but at all times, a certain range of magmas could be tapped from a reservoir by volcanic processes. The mantle sources and magma genesis of Troodos magmas will be discussed in more detail in Chapter 8.

6.3 ARE EARLIER SUBDIVISIONS OF THE EXTRUSIVE SERIES STILL JUSTIFIED?

6.3.1 DIVISION INTO UPPER AND LOWER PILLOW LAVAS

Earlier studies subdivided the extrusive series of the Troodos ophiolite into Basal Group, Lower Pillow Lavas, and Upper Pillow Lavas (Fig. 6.12). These divisions were based on primary and secondary features such as color, abundance of phenocrysts, abundance of intrusives, and the assemblage of secondary minerals (Wilson, 1959, Bear, 1960, Gass, 1960) (Table 6.2).

Gass & Smewing (1973) combined Basal Group and Lower Pillow Lavas into the Axis sequence (often called Lower Pillow Lavas), suggesting they were formed by essentially continuous volcanic activity. Gass & Smewing (1973) also suggested that the Axis sequence formed at a spreading axis at a constructive plate margin, the rocks being metamorphosed to greenschist and zeolite facies. Subsequently, in an off-axis environment, the Upper Pillow Lavas were erupted and now overlie the axis sequence unconformably. Gass & Smewing (1973) claimed that celadonite and chalcedony are absent in the Upper Pillow Lavas but common in the Axis Sequence, whereas the zeolites nathrolite and gmelinite are only present in the Upper Pillow Lavas but not in the Axis Sequence. They found that the break in metamorphic facies often coincided with an erosional unconformity between Upper Pillow Lavas and Axis Sequence. Smewing (1975) observed the erosional unconformity and metamorphic boundary between Upper Pillows Lavas and Lower Pillow Lavas in the Kamara Potamos (Fig. 2.15). Gass & Smewing (1973) described erosional conglomerates and a feeder dike, truncated by erosion, at this location.

The present study revealed that the erosional unconformity and metamorphic boundary between Upper Pillows Lavas and Lower Pillow Lavas in the Kamara Potamos (Fig. 2.15) described by Smewing (1975) and Gass & Smewing (1973) is identical with the boundary between stratigraphic units C (sheet flows) and Unit B (pillows and large lava tubes) (Fig. 2.2g, 2.15), i.e. the boundary between two volcanic edifices. The erosional conglomerate mentioned by Gass & Smewing (1973) is a volcanic breccia, consisting of hyaloclastite. The freshness of this

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Table 6.2. Characteristics of Upper and Lower Pillow Lavas (after Wilson, 1959, Bear, 1960, Gass, 1960)

Upper pillow lavas:

1. Absence or scarcity of contemporaneous intrusives, particularly sills
2. Local pinkish alteration
3. Abundance of olivine phenocrysts, often replaced by calcite
4. Zeolites in vesicles, absence of celadonite

Lower Pillow Lavas:

1. Abundance of contemporaneous intrusives
 2. Abundant volcanic breccia
 3. Celadonite as secondary mineral
 4. Chalcedony, opal and zeolites in vesicles
 5. Lack of olivine phenocrysts
- =====

hyaloclastite layer precludes a long term exposure to sea water at the ocean floor. The "truncated" feeder dike feeds the overlying pillows of unit B without a break (section 2.3). These observations preclude a long time hiatus between the eruption of the stratigraphic units C and B, and the erosional surface cannot be confirmed in this location.

Alteration and formation of secondary mineral phases in the extrusives depends on the cooling unit type, e.g. pillow lava or sheet flow, and not on the relative position in the stratigraphic sequence (this study and Gillis & Robinson, 1985). Celadonite and chalcedony are common in sheet flows, whereas zeolites such as analcime, nathrolite and gmelinite are abundant in pillow lavas (Gillis & Robinson, 1985). It is therefore not surprising that pillow lavas of unit B in the Kamara Potamos (Upper Pillow Lavas after the division of Gass & Smewing (1973)) show zeolite alteration, and sheet flows of the underlying unit C (Lower Pillow Lavas after Gass & Smewing, (1973)) have chalcedony and celadonite as secondary phases. However, celadonite was also found higher up in the section in units A and B (Upper Pillow Lavas after Gass & Smewing (1973)) on large lava tubes

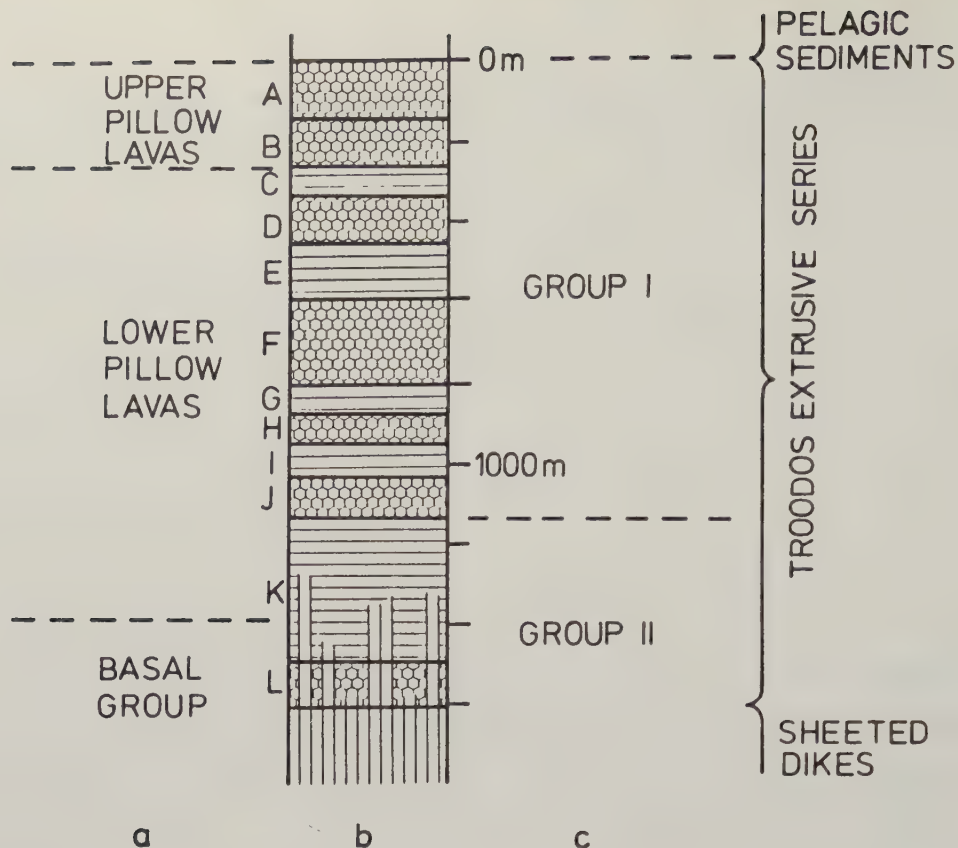


Fig. 6.12. Schematic stratigraphic section through the extrusive series with earlier divisions. a: after Smewing (1975); b: present study, stratigraphic units are indicated; c: Robinson et al. (1983).

with cooling columns similar to those of sheet flows (Fig. 2.15). The zeolites nathrolite and gmelinite are found below the Upper/Lower Pillow Lava boundary, in all lithologic units containing pillow lavas. There is no systematic increase in the degree of alteration and no consistent stratigraphic or metamorphic boundary can be drawn on the basis of secondary mineral distribution (Gillis & Robinson, 1985).

The pinkish pervasive alteration with calcite replacing olivine phenocrysts is interpreted to be due to prolonged ocean floor alteration (Schmincke et al., 1983, Gillis & Robinson, 1985, and this study) and superimposed on the sea floor alteration of the bulk of the volcanics. The entire sequence was erupted without breaks of longer duration, and the lavas were covered soon by new volcanics. Only the lavas erupted at the end of the volcanic activity (unit A) were exposed to seawater at the sea floor long enough to develop this type of alteration.

Further criteria of distinction between Upper and Lower Pillow Lavas were the abundance of dikes and volcanic breccia (both more common in the Lower Pillow Lavas) and the presence of olivine phenocrysts in the Upper Pillow Lavas and their absence in the Lower Pillow Lavas. In the Akaki River section, these features do not change at a specific stratigraphic depth, but gradually, and exceptions exist, e.g. phyrlic lavas are exposed in unit D (Lower Pillow Lavas), and aphyric lavas are found in unit A (Upper Pillow Lavas).

In summary, the present study is only partially consistent with the division into Upper and Lower Pillow Lavas based on abundance of phenocrysts and intrusives, and the assemblage of secondary minerals as proposed by Wilson (1959), Bear (1960), Gass (1960), Gass & Smewing (1973), and Smewing (1975).

6.3.2 DIVISION INTO CHEMICAL GROUPS

Robinson et al. (1983), and later, Bednarz et al. (pers. comm.) have suggested a stratigraphic and chemical division into a lower andesite-rhyodacite series of arc tholeiitic affinity and an overlying more mafic series with depleted arc tholeiite affinity for the extrusive series of the northern flank of the ophiolite. The stratigraphic level of this new geochemical boundary is variable and usually lower than the old Upper/Lower Pillow Lava boundary.

Robinson et al. (1983) and Bednarz et al. (pers. comm.) divide the volcanics into two chemically distinct groups, corresponding closely to the petrographic division proposed by Robinson et al. (1983)

1. Basalt to basaltic andesite suite (8.5 to 3.9% MgO), with lower TiO_2 , FeO^* , and higher MgO for a given SiO_2 , containing microphenocrysts of olivine and clinopyroxene (upper part of the section)
2. Andesite - dacite - rhyodacite suite (3.8 to .25% MgO), containing plagioclase, clinopyroxene and titanomagnetite (lower part of the section)

Robinson et al. (1983) and Bednarz et al. (pers. comm.) interpreted the compositional variations within these groups as consistent with fractional crystallization.

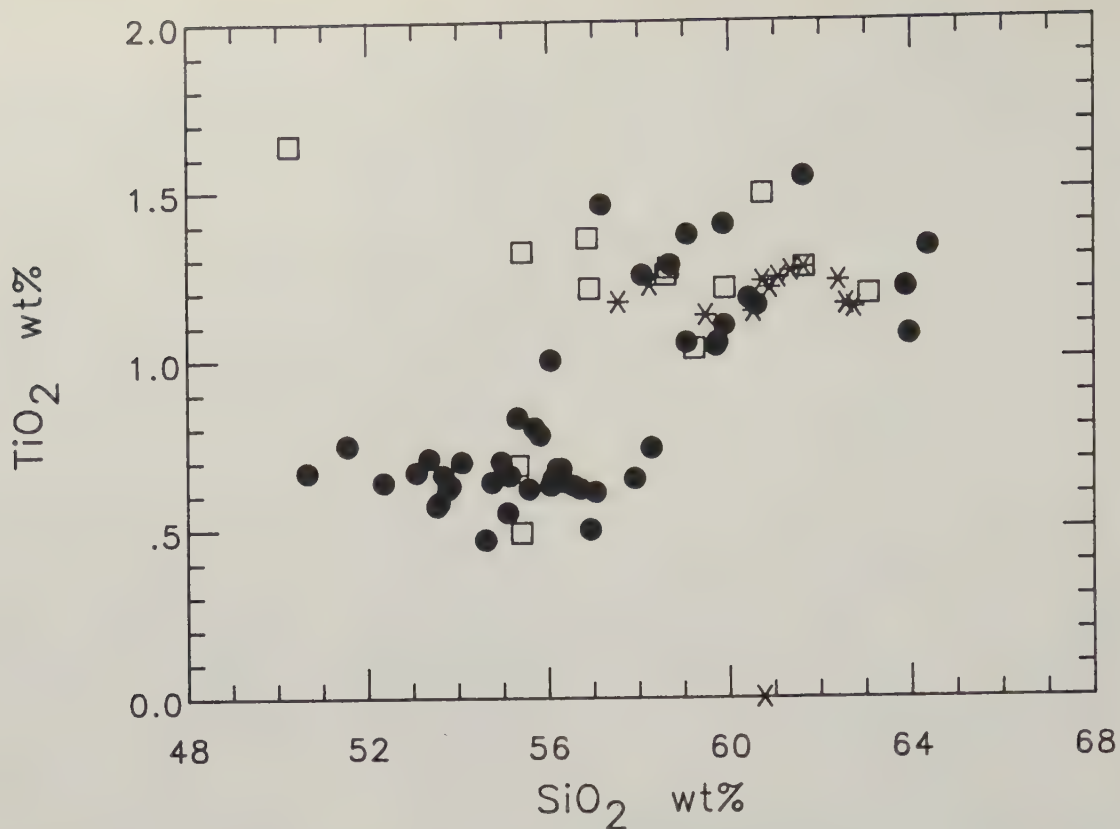


Fig. 6.13. SiO_2 versus TiO_2 for extrusive Troodos glasses. Present study (dots), Bednarz (pers. comm.) (squares), Robinson et al. (1983) (stars).

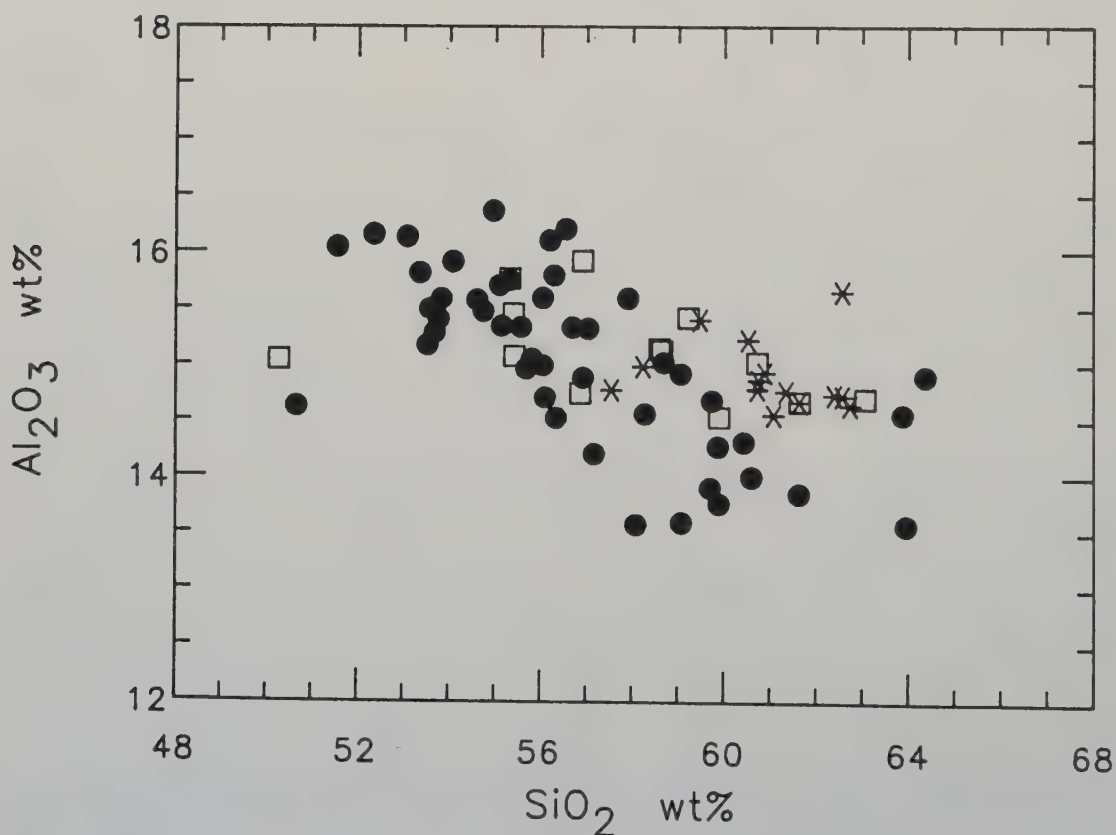


Fig. 6.14. SiO_2 versus Al_2O_3 for extrusive Troodos glasses. Present study (dots), Bednarz (pers. comm.) (squares), Robinson et al. (1983) (stars).

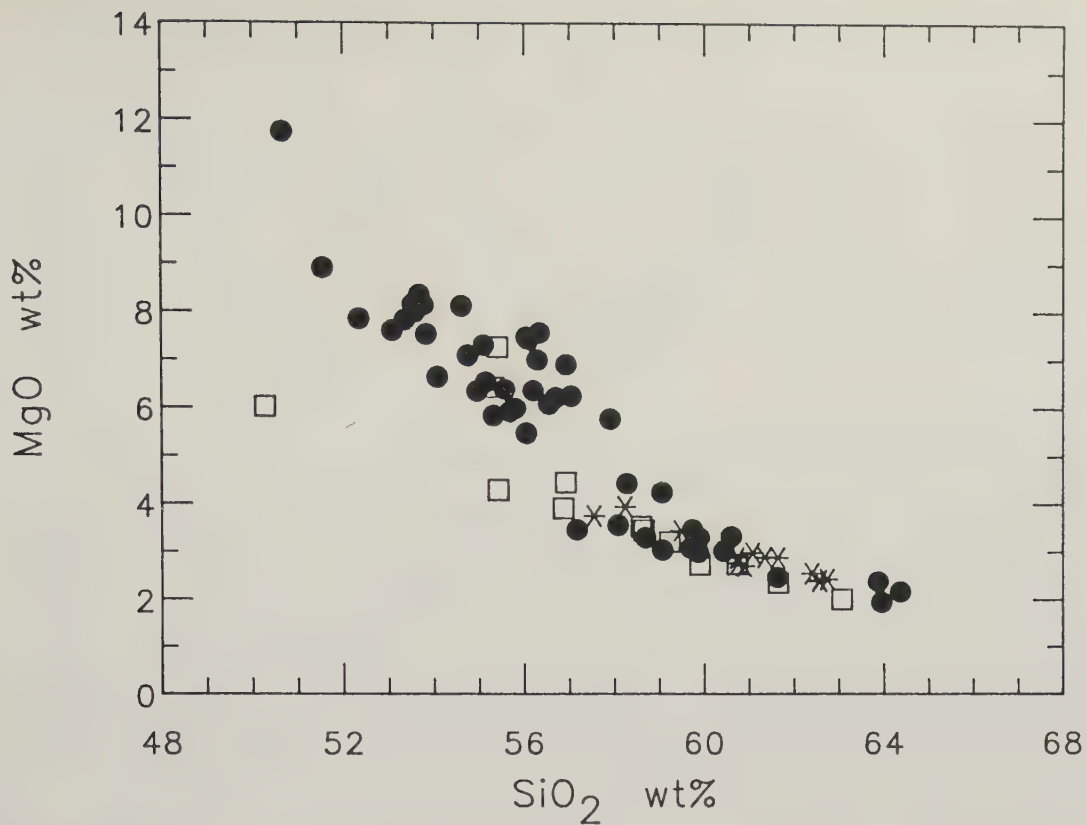


Fig. 6.15. SiO_2 versus MgO for extrusive Troodos glasses. Present study (dots), Bednarz (pers. comm.) (squares), Robinson et al. (1983) (stars).

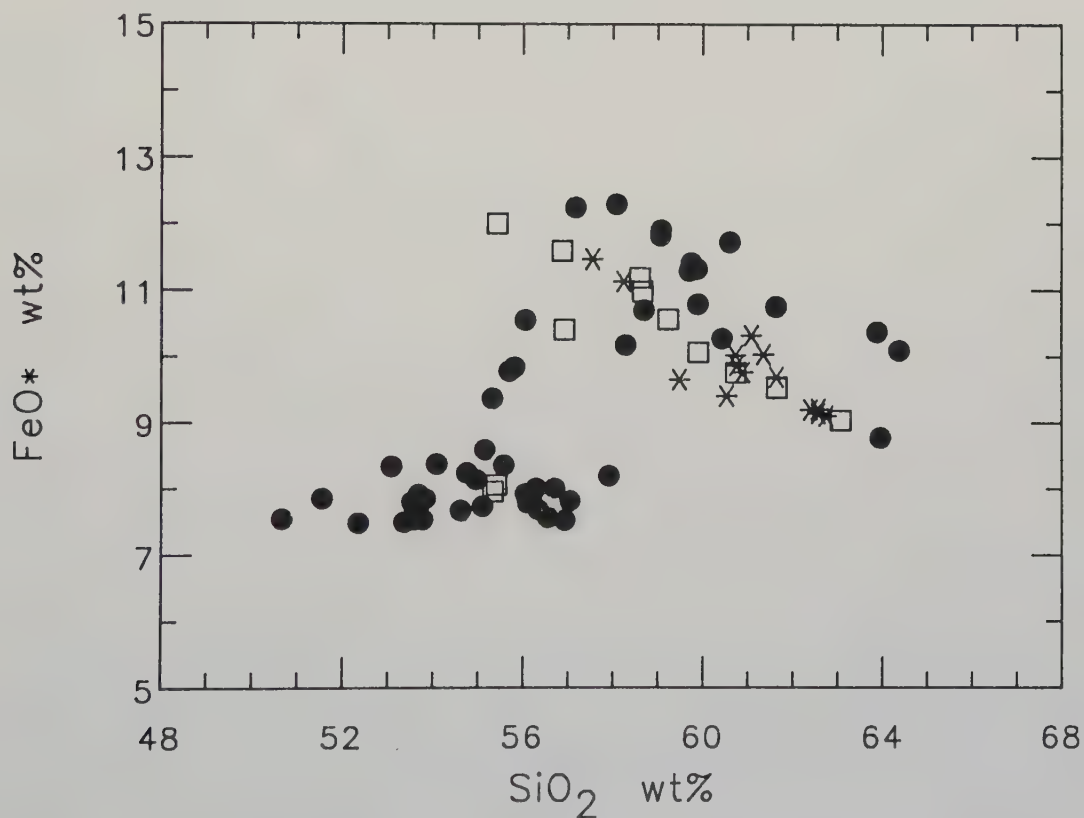


Fig. 6.16. SiO_2 versus FeO^* for extrusive Troodos glasses. Present study (dots), Bednarz (pers. comm.) (squares), Robinson et al. (1983) (stars).

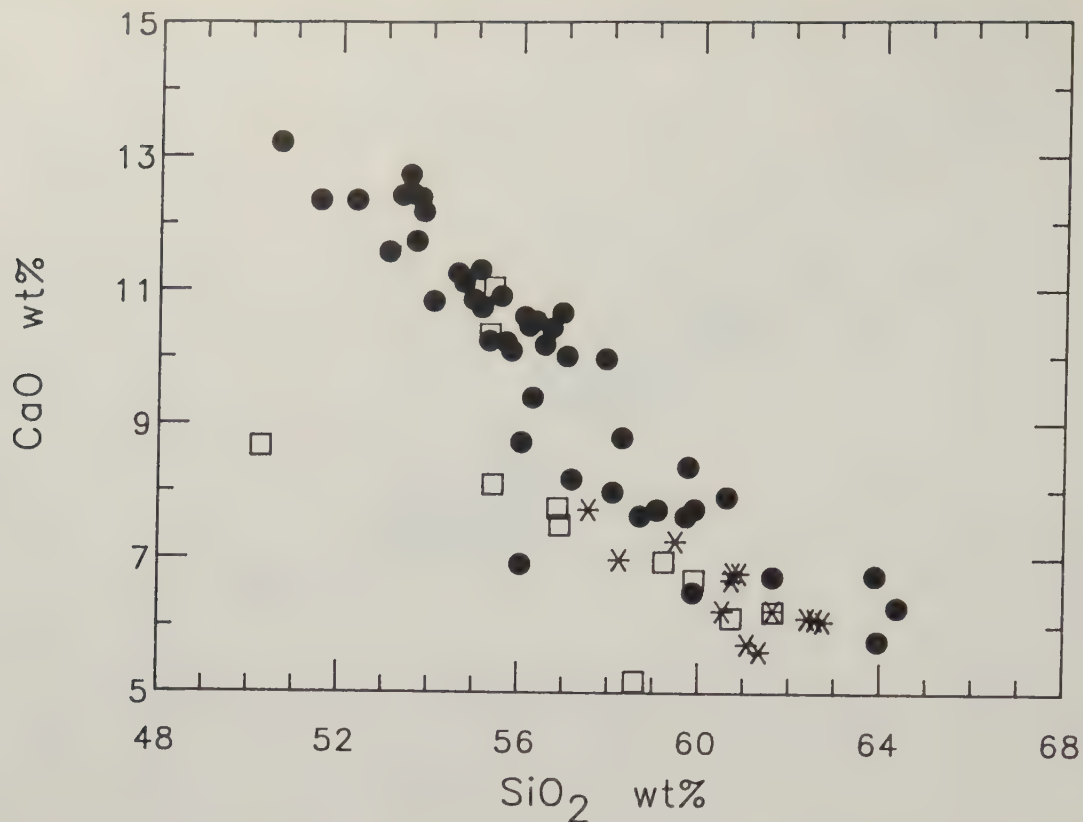


Fig. 6.17. SiO_2 versus CaO for extrusive Troodos glasses. Present study (dots), Bednarz (pers. comm.) (squares), Robinson et al. (1983) (stars).

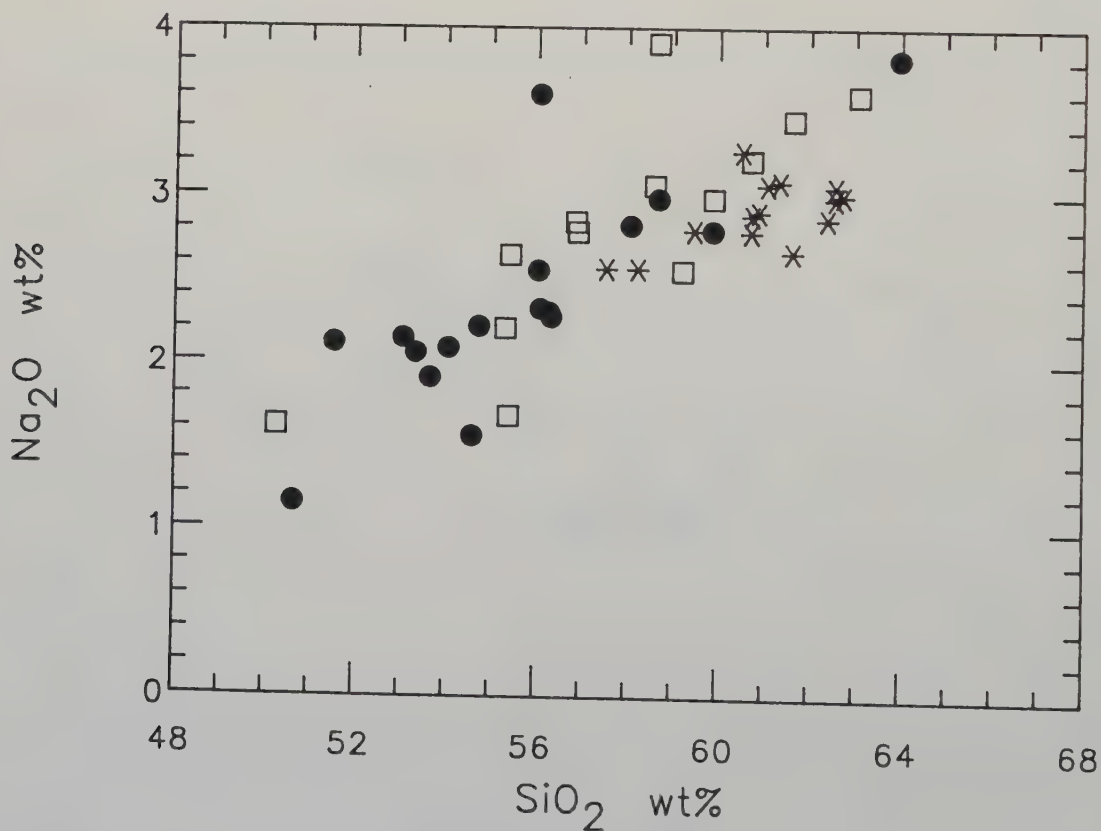


Fig. 6.18. SiO_2 versus Na_2O for extrusive Troodos glasses. Present study (dots), Bednarz (pers. comm.) (squares), Robinson et al. (1983) (stars).

The present study has shown that the petrography of the extrusives in the Akaki River Canyon is more variable than described by Robinson et al. (1983). Several associations of phenocrysts have been found, cpx-plag-opx, ol-cpx, ol, ol-cpx-plag, and plag, in order of decreasing abundance (see Chapter 3). No obvious groups could be distinguished on the base of petrography.

The extrusive rocks from the Akaki River section show a broad correlation of major element compositions with stratigraphy, from more differentiated compositions at the base to more mafic volcanics at the top (Fig. 6.1 - 6.4). However, no sharp break in chemistry is observed in the Akaki River canyon. Dominantly mafic lavas occur at the top and differentiated ones at the base, but at any given level in the stratigraphy, a significant variation of compositions is observed.

For an evaluation of the division into chemically distinct groups proposed by Robinson et al. (1983), and Bednarz et al. (pers. comm.),

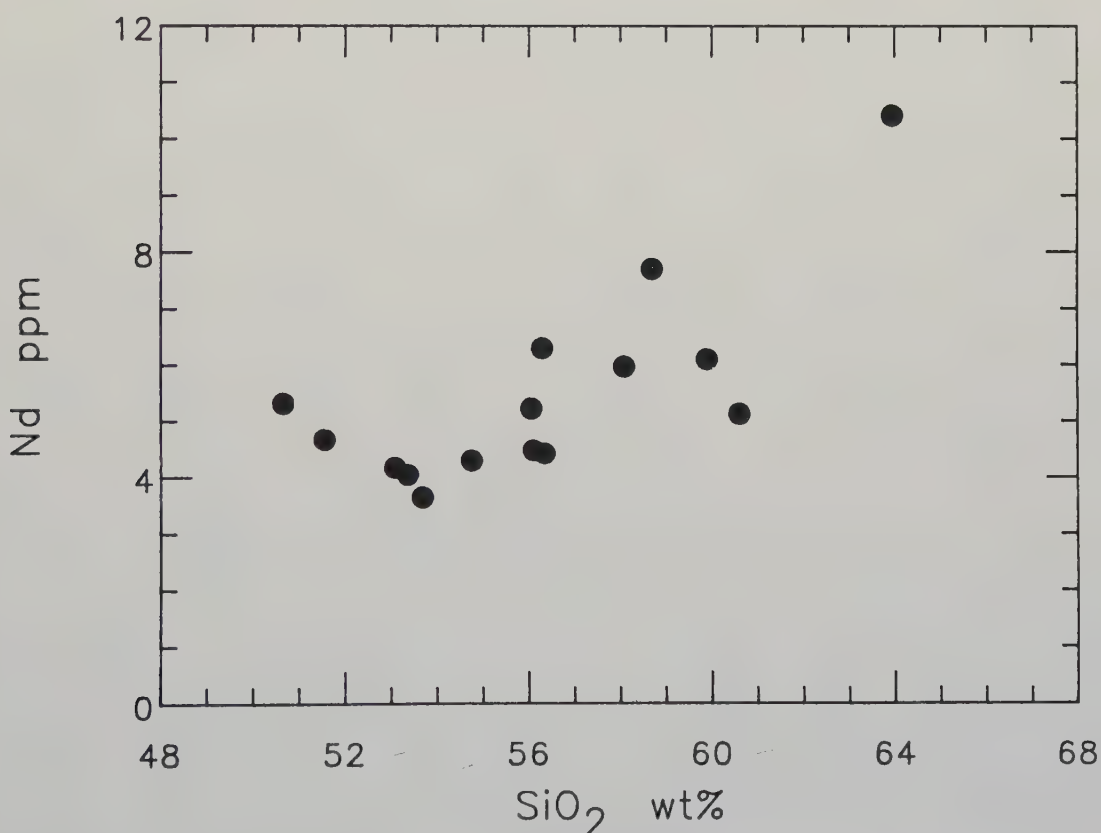


Fig. 6.19. Nd versus SiO₂ for extrusive glasses (dots).

the available glass data will be considered. Robinson et al. (1983) collected glass samples from various locations in the Troodos ophiolite. Bednarz (pers. comm.) analyzed volcanic glasses from sections through the extrusive series neighboring the Akaki River canyon and drill cores, whereas samples for this study are mostly from the Akaki River canyon.

The chemical division was proposed for SiO_2 , FeO^* , and TiO_2 . Major element compositions of all Akaki glasses are plotted against SiO_2 (Fig. 6.13 - 6.18). Only TiO_2 shows a clear bimodal distribution, all other major and trace elements show broad correlations with SiO_2 , with a certain variation at any given concentration of SiO_2 , and no obvious grouping. As example for trace elements Nd and Ba/Rb versus SiO_2 are shown (Fig. 6.8, 6.19).

It must be emphasized that diagrams such as Fig. 6.13 - 6.18, in which all available data are plotted, have no a priori statistical significance, because they may be severely affected by sampling bias. For example, the majority of samples obtained from the drill cores CY2 and CY2a represent a total of only 30m of stratigraphic section. Extrusive analyses of samples from these cores would therefore tend to produce dense clusters of data points, which cannot be pooled indiscriminantly with other data. In order to minimize the possibility of sampling bias, the Akaki River section was subdivided into stratigraphic intervals of 50 m. The mean and standard deviation of all analyses within each interval were determined. These values are plotted against the stratigraphic depth for SiO_2 , FeO , and TiO_2 (Fig. 6.20 - 6.22).

The means of SiO_2 and FeO^* show a continuous increase with increasing stratigraphic depth (Fig. 6.21 - 6.22) without obvious breaks. TiO_2 concentrations are mostly between 0.6 and 1.0% down to a depth of 1200m. Below this, TiO_2 concentrations start at 1.3% but decrease again to less than 1% with increasing stratigraphic depth (Fig. 6.20).

Further, the frequencies of the means of SiO_2 , FeO^* , and TiO_2 were plotted in Fig. 6.23 for Akaki volcanics. Samples from the upper 1200 m of the sequence are distinguished from those of the lower part

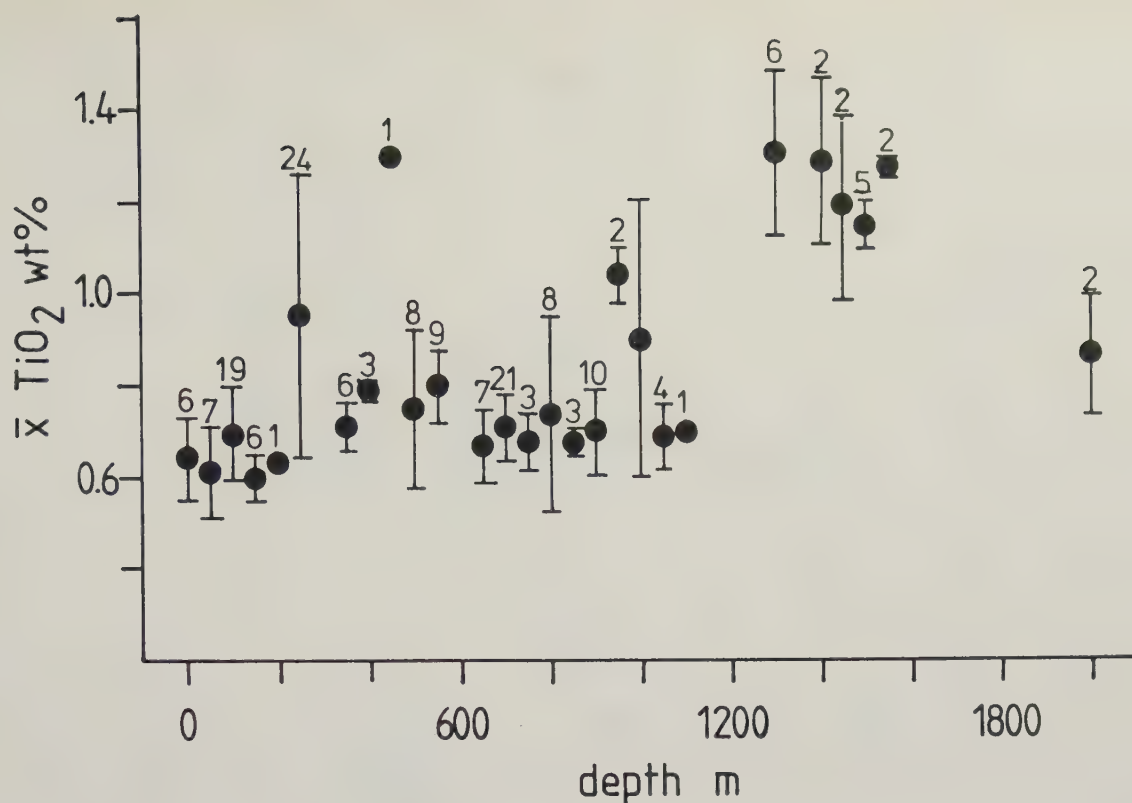


Fig. 6.20. Means of TiO₂ concentrations for extrusives, calculated for stratigraphic intervals of 50 m from the Akaki River canyon. Numbers indicate number of samples, error bars show standard deviation.

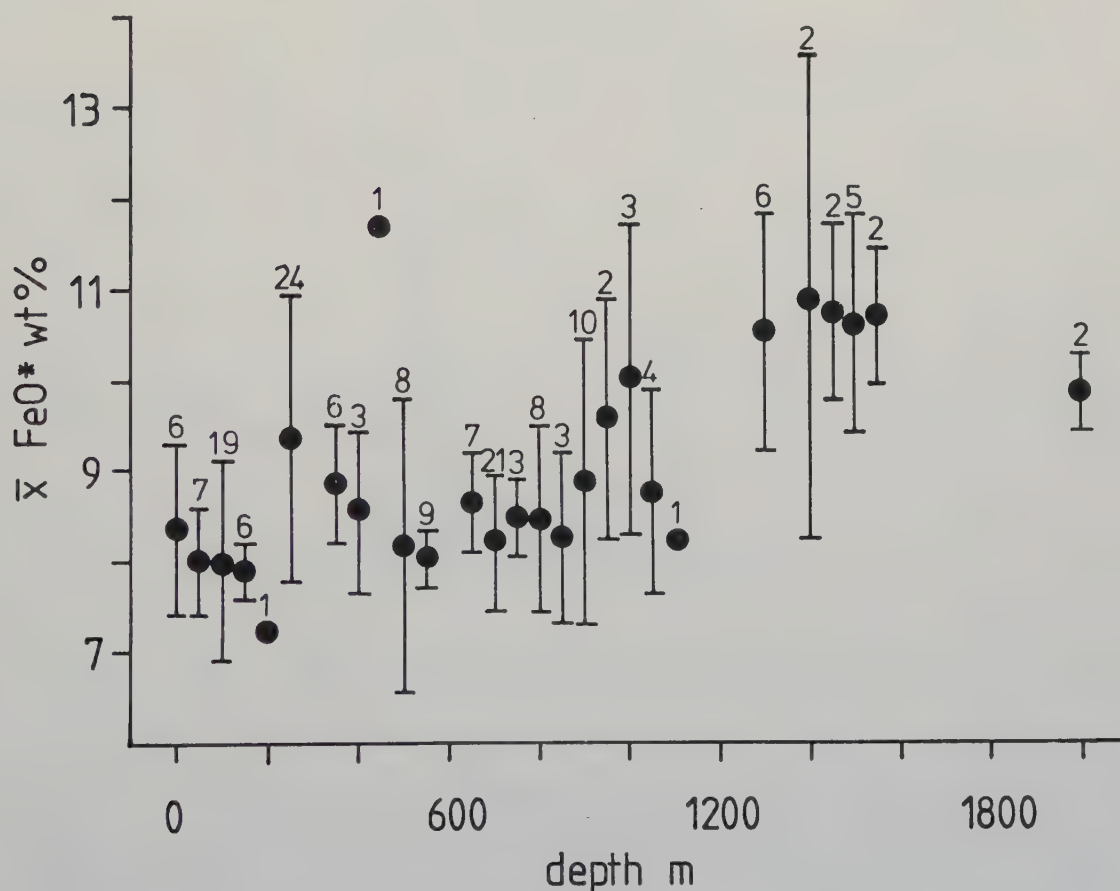


Fig. 6.21. Means of FeO* concentrations for extrusives, calculated for stratigraphic intervals of 50 m from the Akaki River canyon. Numbers indicate number of samples, error bars show standard deviation.

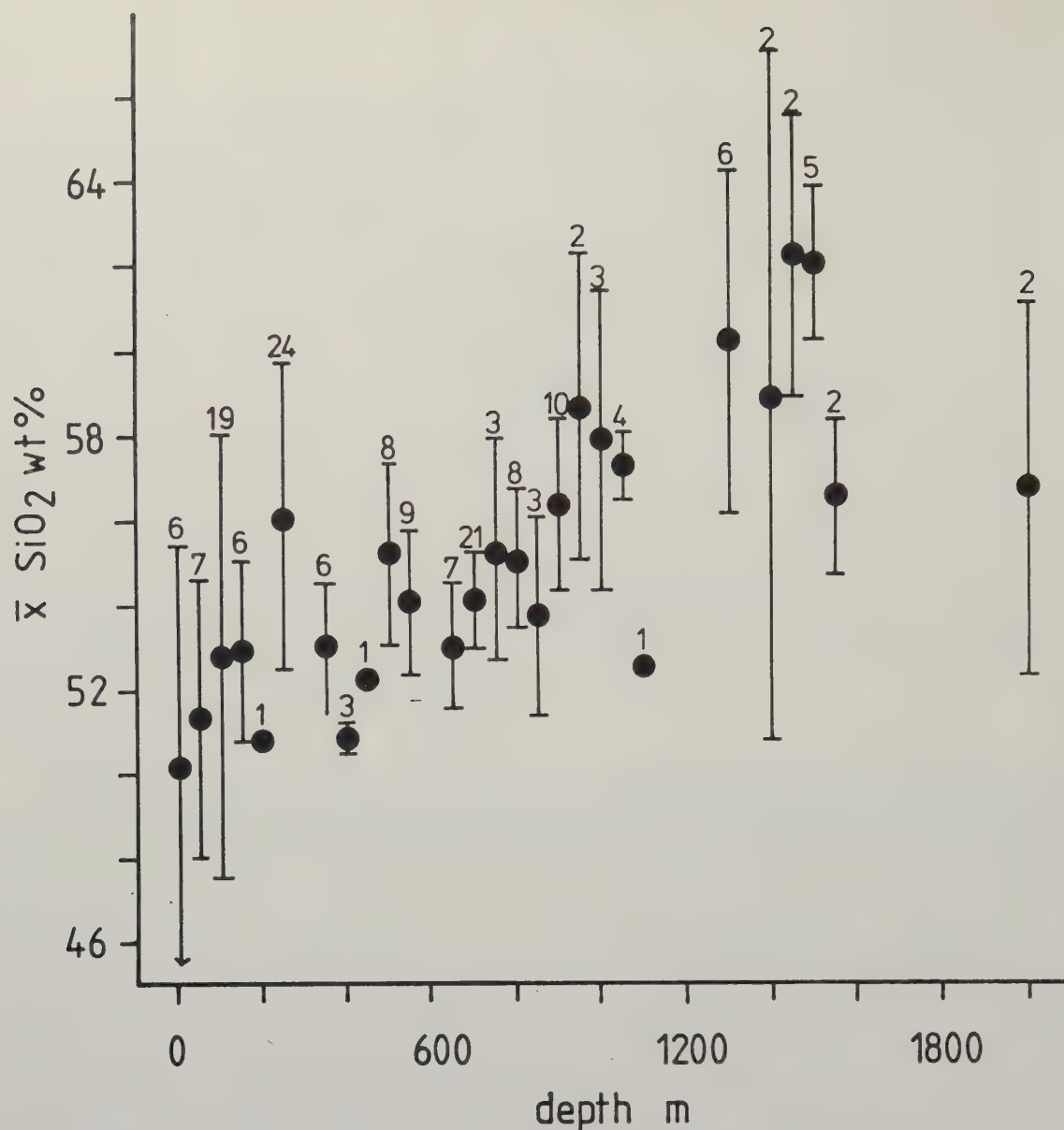


Fig. 6.22. Means of SiO₂ concentrations for extrusives, calculated for stratigraphic intervals of 50 m from the Akaki River canyon. Numbers indicate number of samples, error bars show standard deviation.

in the diagram. The distribution of the means of SiO₂ shows a maximum at 52 to 53%. The compositions of upper and lower part of the sequence are overlapping, consistent with the findings of Fig. 6.22. For FeO*, two maxima are present for the Akaki samples. The lower part of the section is higher in FeO* than the upper part with an overlap, again consistent with observations made in Fig. 6.21. TiO₂ values also show two maxima, a larger one at 0.6 to 0.8%, the other one at 1.1 to 1.4%. Again, the upper part of the section shows lower values than the lower

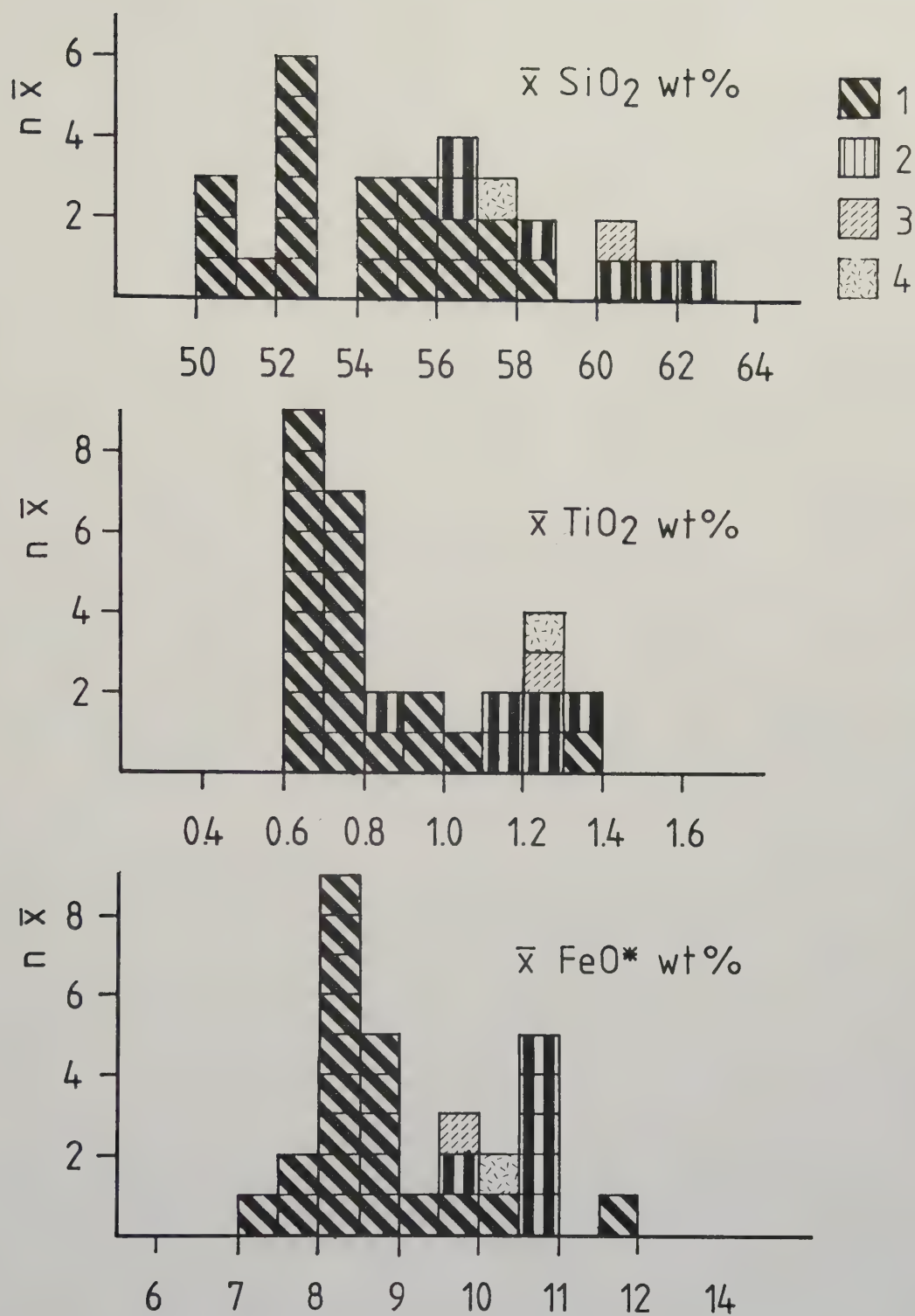


Fig. 6.23. Frequencies of means of SiO₂, TiO₂, and FeO* concentrations. 1: Akaki extrusives above 1200 m depth, 2: Akaki extrusives below 1200 m depth, 3: drill cores of holes CY2, CY2a (Bednarz, pers.comm.), 4: Pediaeos Canyon samples (Bednarz, pers. comm.).

part (see also Fig. 6.20). The data from the Pedaeios canyon and drill holes CY 2 and 2a show high SiO_2 , FeO^* and TiO_2 values.

In summary, a fairly clearly defined chemo-stratigraphic break occurs at 1200m depth for TiO_2 . This break may also be present but is rather indistinct for FeO . All other major element abundances, particularly SiO_2 , MgO and Ca show gradual changes with stratigraphic depth. In particular, a stratigraphic classification of the volcanics on the basis of SiO_2 is not possible in the Akaki River section and can therefore not be generally valid for the Troodos complex, even if an SiO_2 based stratigraphy were found to be more clearly developed in other parts of the complex. The TiO_2 stratigraphy, though valid statistically in the Akaki River section, has exceptions on both sides of the break. It would therefore appear to be rather risky to classify unknown samples stratigraphically on the basis of TiO_2 content. On the other hand, this analysis has confirmed the broad stratigraphic correlation of more highly differentiated (high TiO_2 , SiO_2 , FeO , low MgO) volcanics in the lower part of the section and less differentiated, more basaltic-andesitic rocks in the upper part.

6.4 CONCLUSIONS

There is a significant correlation of chemical composition with stratigraphic depth in the Akaki River section. The lower part of the section contains dominantly more differentiated extrusives with higher TiO_2 contents, and the upper part more mafic volcanics with lower TiO_2 contents. In addition, a significant variation in chemical compositions is found at any stratigraphic level.

The volcanologic model proposed that the extrusives of each stratigraphic unit were erupted in a relatively short period of time, followed by a break in volcanic activity. However, the chemical composition of the extrusives within these stratigraphic units is heterogeneous in major and trace element concentrations as well as in isotopic compositions. An eruption forming a stratigraphic unit may contain magmas with heterogeneous source characteristics, indicating that one or several magma chambers may be replenished with similar, but heterogeneous magmas. The volcanologic model of the extrusion mechanism is independent of the chemical compositions of the lavas.

The earlier subdivision of the extrusive series into Upper and Lower Pillow Lavas is only partially consistent with the findings in the Akaki River canyon. The division into a lower andesite-rhyolite and overlying more mafic series could only be confirmed for TiO_2 and FeO^* by this study. For all other elements, no strict stratigraphical and/or chemical groups are observed when the available glass data from the extrusive series are considered.

CHAPTER 7. TECTONIC SETTING

7.1 INTRODUCTION

Ophiolites are widely believed to represent fragments of oceanic crust formed at constructive plate margins. As a result, petrologists and geophysicists have drawn on ophiolites to constrain the nature of oceanic crust formed at major oceanic basin spreading ridges. The Troodos ophiolite is one of the earlier recognized and best documented examples, and was the subject of pioneering papers by Gass (1968), Moores & Vine (1971), and Gass & Smewing (1973).

It is now recognized that many ophiolites have physical, petrological and geochemical characteristics different from those observed at modern, major ocean basin spreading ridges. Differences include the smaller thickness of the crustal section in ophiolites (Coleman, 1977, Moores, 1982), the common occurrence of more highly differentiated rock types such as andesites and dacites, and differences in chemical composition between ophiolites and normal oceanic crust (Miyashiro, 1973, Pearce, 1980, Pearce et al., 1981, Alabaster et al., 1982, McCulloch & Cameron, 1983).

Back-arc or marginal basins are possible alternative sites for generation of oceanic crust. Yet another possible scenario is that rifting/spreading events take place in the early stages of island arc evolution, above subduction zones at destructive plate margins, creating oceanic crust formed in a tensional environment.

The problem of discrimination between different tectonic settings (constructive versus destructive plate margins) is difficult to solve for ancient volcanics. Several discrimination diagrams have been proposed in the past. These diagrams are based on the differences in chemical composition, observed for recent volcanics, originated in different tectonic settings, for example the relative abundances of Ti, Th, Zr, Hf, Y, and Sr (e.g. Pearce & Cann, 1973, Miyashiro, 1973, T.H. Pearce et al., 1975, Floyd & Winchester, 1975, Wood et al., 1979, Shervais, 1982). However, several points must be considered when this method of discrimination is used. The diagrams are empirical, in that they are based on recent volcanics from known tectonic settings, however, the causes for the observed chemical differences are still

poorly understood. In addition, the discrimination is based on fresh, mostly basaltic volcanics. This implies that for altered volcanics only those elements which are immobile during secondary alteration can be used. Fractionated samples such as andesites and dacites may not be classified with certainty, because one of the discriminating elements, e.g. Ti, may no longer be incompatible and trace element ratios with Ti are no longer characteristic of the magma source and tectonic environment but may be controlled by fractional crystallization. Lastly, it is not known if these chemical differences between tectonic settings and the compositions of recent volcanics observed today were also present in the past of Earth's history. Thus, the discrimination between tectonic settings is problematic for ancient volcanics.

On the basis of geochemical data several workers have proposed that the Troodos ophiolite formed in an island arc (Miyashiro, 1973) or, less specifically, in an environment influenced by a subduction zone (supra-subduction zone) (Pearce, 1975, 1980, McCulloch & Cameron, 1983, Robinson et al., 1983, Schmincke et al., 1983).

Previous attempts to determine the tectonic environment origin of the Troodos complex were often complicated by the effects of post-eruptive alteration and only the immobile HFS and REE elements could be used. The present study, however, uses the chemical compositions of fresh glasses unaffected by secondary alteration representing the original compositions of the magmas (see chapter 5). Thus, not only the immobile elements but also the alteration-sensitive elements such as alkalis and the isotopic compositions of Sr and oxygen can be used to solve the problem. Comparison of these data with published data for fresh modern volcanics from constructive and destructive plate margins allows the origin of the Troodos ophiolite to be constrained to the extent that any such chemical constraint is valid.

Oceanic volcanics comprise several different types including ocean island basalts, mid-ocean ridge basalts, and subduction zone-related volcanics. However, the discussion can be restricted by considering only oceanic volcanics with similar REE-patterns to those of Troodos, i.e. characterized by light REE depletion. In this respect, at least at first glance, Troodos lavas resemble those of N-MORB (Kay & Senechal, 1976), island arc tholeiites (Jakes & Gill, 1970), and some

marginal basin basalts (Saunders & Tarney, 1984), but not ocean island basalt. In this chapter, these types of volcanics will be compared to Troodos glasses with respect to petrography, major and trace elements and isotopic compositions.

7.2 PETROGRAPHY

Petrographic characteristics in modern oceanic basalts vary in different tectonic settings. In MORB and most marginal basin basalts the crystallization sequence is olivine - plagioclase - clinopyroxene, but clinopyroxene is rare (Cameron et al., 1980, Natland & Tarney, 1981). In contrast, the crystallization sequence in island arc tholeiites from the Mariana arc is olivine - clinopyroxene - plagioclase. These volcanics are mostly aphyric, and have occasional microphenocrysts of clinopyroxene and plagioclase in a glassy mesostasis with quenched microlites (Natland & Tarney, 1981). Troodos volcanics show the same characteristics as island arc tholeiites, including the quench textures observed on plagioclase and clinopyroxene microphenocrysts. Another characteristic of island arc tholeiites, fine-grained opaque minerals, are also common in Troodos lavas. Troodos lavas are highly vesicular, comparable to those of the Mariana arc (Natland & Tarney, 1981), whereas MORB basalts have a low vesicle content.

7.3 MAJOR ELEMENTS

As has been previously discussed by Myiashiro (1973), Robinson et al. (1983) and Schmincke et al. (1983), the major element characteristics of the Troodos glasses are distinct from those of N-MORB. Averages of typical N-MORB glasses (Garcia et al., 1979, Melson et al., 1980, Muenow et al., 1980, Hofmann et al., in prep.), and back-arc basalt compositions (Saunders & Tarney, 1979, Jenner et al., 1987) are given in Table 7.1 and 7.2. Compared with N-MORB and typical back-arc basin volcanics at similar MgO concentrations, Troodos glasses have significantly lower TiO_2 , and higher SiO_2 and K_2O concentrations. The high K_2O concentrations in the back-arc basin basalts may be affected by secondary alteration. Troodos lavas show similar major element compositions to those found in island arc tholeiites such as those from Fiji (Gill, 1970), Tonga (Ewart et al., 1973), the Palau Kyushu remnant arc (Wood et al., 1980a,b), and those of back arc basin basalts from Dredge 24, Scotia Sea (Saunders & Tarney, 1979). The differences are

Table 7.1. Major element compositions of Troodos glasses, MORB, island arc tholeiite, and back arc basin basalts

	1		2		3	4	5	6
	Troodos std.		BAB		D24.14	MORB	Ata	Valu Fa
	maf.av. dev.		Scotia S.		Scotia S.		8-9	D1-5
	%		1-5 av.					
SiO ₂	54.36	3.1	50.32		53.84	50.22	54.10	56.79
TiO ₂	.65	13.8	1.21		.61	1.45	.75	1.39
Al ₂ O ₃	15.27	4.8	17.15		14.51	15.75	17.30	14.58
FeO*	7.88	3.5	7.55		8.31	9.97	10.08	11.52
MnO	.15	8.7	.16		.17	.17	.21	.22
MgO	7.85	7.3	7.38		7.71	7.94	4.44	3.74
CaO	11.44	6.2	10.93		10.80	11.48	9.97	7.66
Na ₂ O	2.11	8.1	3.08		1.79	2.66	2.36	3.37
K ₂ O	.16	22.0	.39		.24	0.083	.62	.52
vol.	2.26	38.5	-		-	0.48	.24	1.59

1. average of mafic Troodos glasses (samples 305, 316, 331, 340, 345, 350, 371, 544) with standard deviation given in %.
2. back-arc basin basalts, Scotia Sea, average of samples 1-5 (Saunders & Tarney, 1979).
3. back-arc basin basalt, Dredge 24, Scotia Sea (Saunders & Tarney, 1979).
4. average of N-MORB basalt glasses (Jochum et al., 1983, 1986, Melson et al., 1980, Delaney et al., 1978, Hofmann et al., in prep.).
5. island arc tholeiite Ata 8-9, Tonga arc (Jenner et al., 1987).
6. back-arc basin andesite D 1-5, Valu Fa ridge (Jenner et al., 1987).

Table 7.2. Abundances of volatile components of sample 316, typical MORB, island arc tholeiite and back arc basin basalt

	1	2	3	4	5
	316	Mariana Arc	Mariana Trough	MORB	Scotia Sea BAB
H ₂ O	2.065	1.020	1.066	.201	.830
CO ₂	.057	.209	.245	.132	.232
S	.052	.082	.006	.117	.053
Cl	.105	.030	.107	.006	.012
F	.011	.031	.103	.023	.024
Total	2.290	1.372	1.527	.479	1.151

1. Troodos glass 316, analysis by M. Garcia, 1986
2. Mariana arc average (Garcia et al., 1979)
3. Mariana Trough average (Garcia et al., 1979)
4. MORB, Mid Atlantic Ridge average (Delaney et al., 1978)
5. Scotia Sea back arc basin, Dredge 20 average (Muenow et al., 1980).

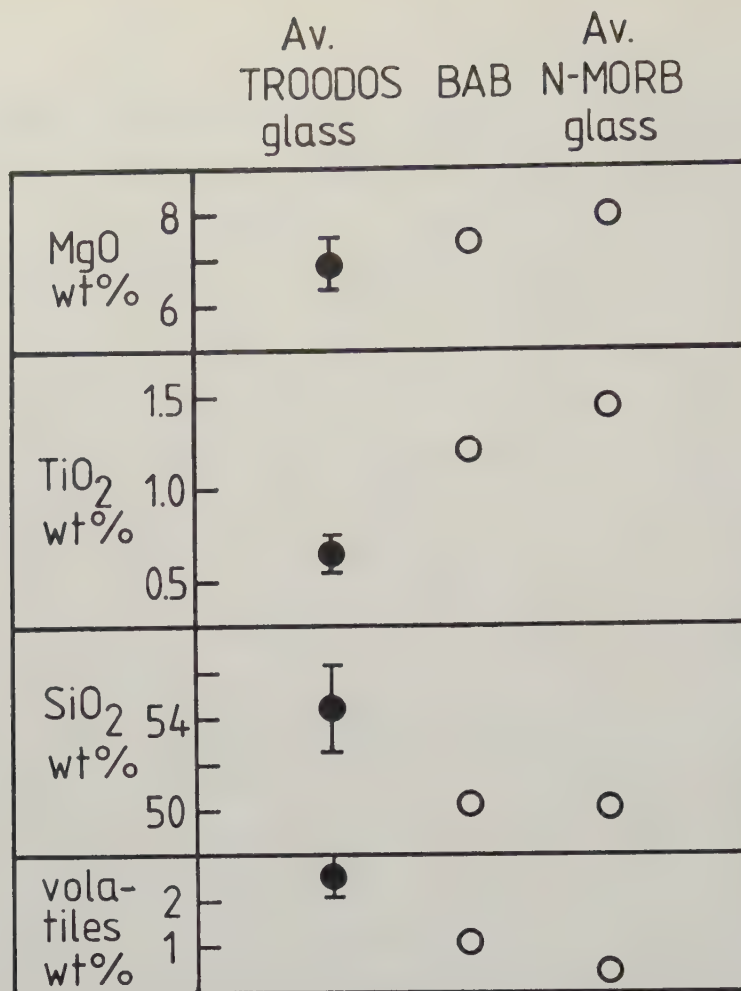


Fig. 7.1. Average of major element compositions of mafic Troodos glasses (samples 305,316,331,340,345,350,371,544) with standard deviation. Back arc basin basalt average Scotia sea (BAB) (Saunders & Tarney, 1979). Average of N-MORB glasses (Jochum et al., 1983, 1986, Melson et al., 1980, Delaney et al., 1978, Hofmann et al., in prep.).

illustrated in Fig. 7.1. Troodos lavas are different from Valu Fa (back arc basin) volcanics, in that they have lower TiO₂ and higher MgO concentrations (Table 7.1).

Abundances of volatile components of Troodos glasses, back arc-basin basalts and island arc volcanics are given in Table 7.2. Troodos values range from 2 to 5%. These values are substantially higher than those found in MORB glasses (ca. 0.4 %), but overlap with those reported for glasses and glass inclusions (1 to 4 %) of back arc and island arc volcanics (Garcia et al., 1979, Muenow et al., 1980, Gill, 1981). The higher volatile contents on supra-subduction zone volcanics are interpreted to be a primary feature of the rocks, and this

interpretation is supported by their higher vesicularity (Garcia et al., 1979, Muenow et al., 1980, Scott et al., 1980, Gill, 1981). Table 7.2 gives the volatile composition of sample 316, analyzed by M. Garcia. The distribution of volatiles is similar to that observed in fresh, subduction zone related volcanics (Garcia et al., 1979).

7.4 TRACE ELEMENTS

The geochemical characteristics of MORB and supra-subduction zone volcanics differ in several ways (e.g Wood et al., 1979, Saunders et al., 1980, Pearce, 1982, Briquieu et al., 1984, Saunders & Tarney, 1984, Pearce et al., 1984, Hofmann et al., 1986), particularly with respect to LFS/HFS and LFS/REE ratios. This is caused by their different magma generation processes.

N-MORB magmas are derived from depleted mantle, whereas subduction zone related magmas have more complex mantle sources. At a converging plate margin, the subducted slab of oceanic crust consists of sediment and oceanic crust and is overlain by a mantle wedge (Fig. 7.2). This mantle wedge has depleted character, similar to the depleted mantle giving rise to N-MORB, but probably even more depleted in incompatible trace elements. It is possible that this depletion is caused by an earlier melting event (Green, 1972, Duncan & Green, 1980). It is widely believed that during subduction incompatible element-rich fluids ascend from the subducted slab and penetrate and modify the composition of the overlying mantle wedge (Gill, 1974, Ringwood, 1974,

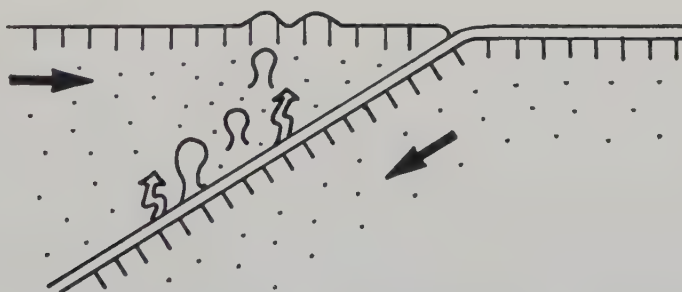


Fig. 7.2. Schematic cross section of a subduction zone. $\equiv$ sediment, $\equiv$ oceanic crust, $\cdot\cdot\cdot\cdot$ depleted mantle, Ω magma derived from the depleted mantle modified by sediment and fluid from the subducted slab, $\star$ fluids from the subducted slab.

This combination gives rise to the subduction zone-related magmas with distinct chemical characteristics from those of N-MORB. In N-MORB, the LFS elements (K, Rb, Cs, Sr, Ba) and Th are depleted relative to the REE and HFS elements (Ta, Nb, Ti, Zr, Hf) (Sun, 1980). The concentration ratios of some of the LFS elements are constant in all N-MORB, namely Ba/Rb, Cs/Rb (Hofmann & White, 1983), and K/U (Jochum et al., 1983).

Subduction zone volcanics are enriched in the LFS element relative to the REE and HFS elements with concentrations of REE and HFS lower than in N-MORB (Sun, 1980). In addition, the ratios between the LFS elements are not constant (White & Patchett, 1984). These features are caused by the modification the subducted slab introduces to the overlying mantle wedge in the subduction zone. The enrichment in LFS over REE and HFS elements and the variety in relative and absolute LFS concentrations may be explained by the variability of LFS concentrations in subducted oceanic sediments and by the high mobility of the LFS elements, so that these elements are transported preferentially over the less soluble REE and HFS elements when incompatible element-rich fluids rise from the subducted slab into the overlying mantle wedge.

Further, all subduction zone volcanics show a depletion of Nb and Ta relative to the REE and HFS elements (Wood et al., 1979, Kay, 1980, Sun, 1980). This has been interpreted to be caused by a mineral phase stable in a subduction zone environment, holding these element back in the magma source, e.g. sphene, rutile, perovskite, or ilmenite. These minerals may incorporate Nb and Ta, and other HFS elements such as Ti, Hf and Zr (Wood et al., 1979, Gill, 1981, 1984, Morris & Hart, 1983, Briquieu et al., 1984). Another possible reason for the depletion of these elements is the fact that Nb and Ta are also strongly depleted relative to the REE in the sediment component of the subducted lithosphere added to the mantle wedge (e.g. Taylor & McLennan, 1985). The addition of a sediment component depleted in Nb and Ta to a mantle source depleted in LFS, REE and HFS elements may also cause a relative depletion of Nb and Ta in the mixture (see chapter 8).

Pearce & Cann (1973) proposed discrimination diagrams which are based on the concentrations of Ti, Zr, Y, and Sr. Most of the Troodos

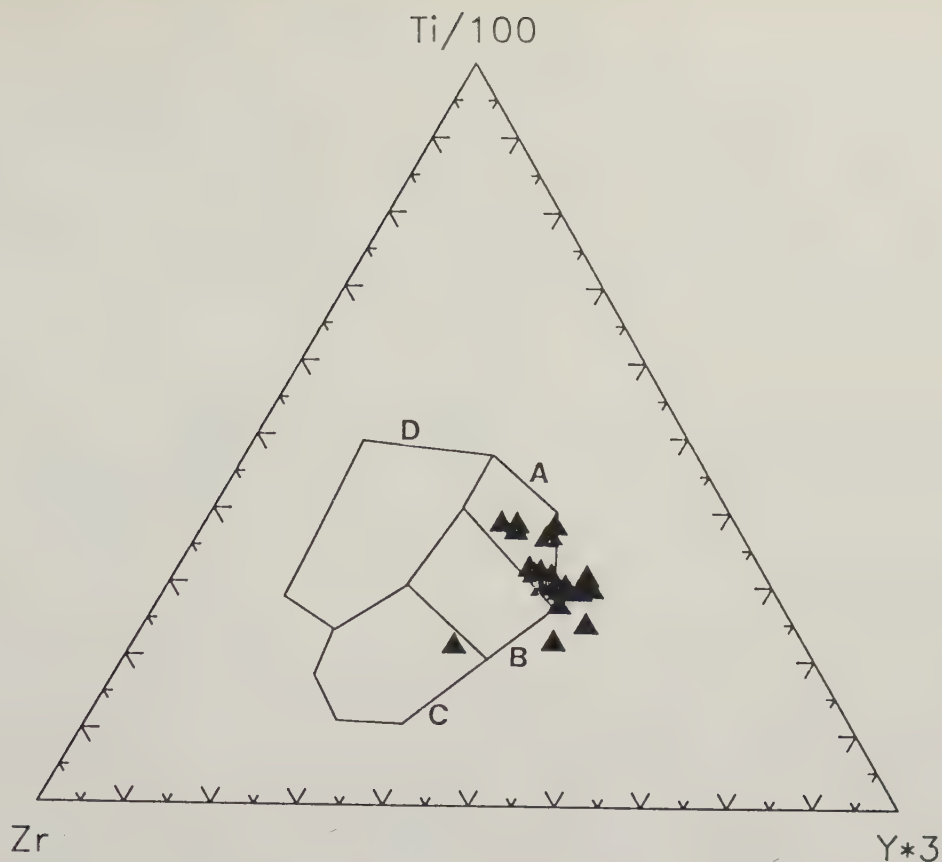


Fig. 7.3. Discrimination diagram after Pearce & Cann (1973) for Troodos glasses (triangles). Fields are: A - LKT, B - OFB, LKT, CAB, C - CAB, D - WPB. LKT: low K-tholeiite, OFB: ocean floor basalt, CAB: calcalkaline basalt, WPB: within plate basalt.

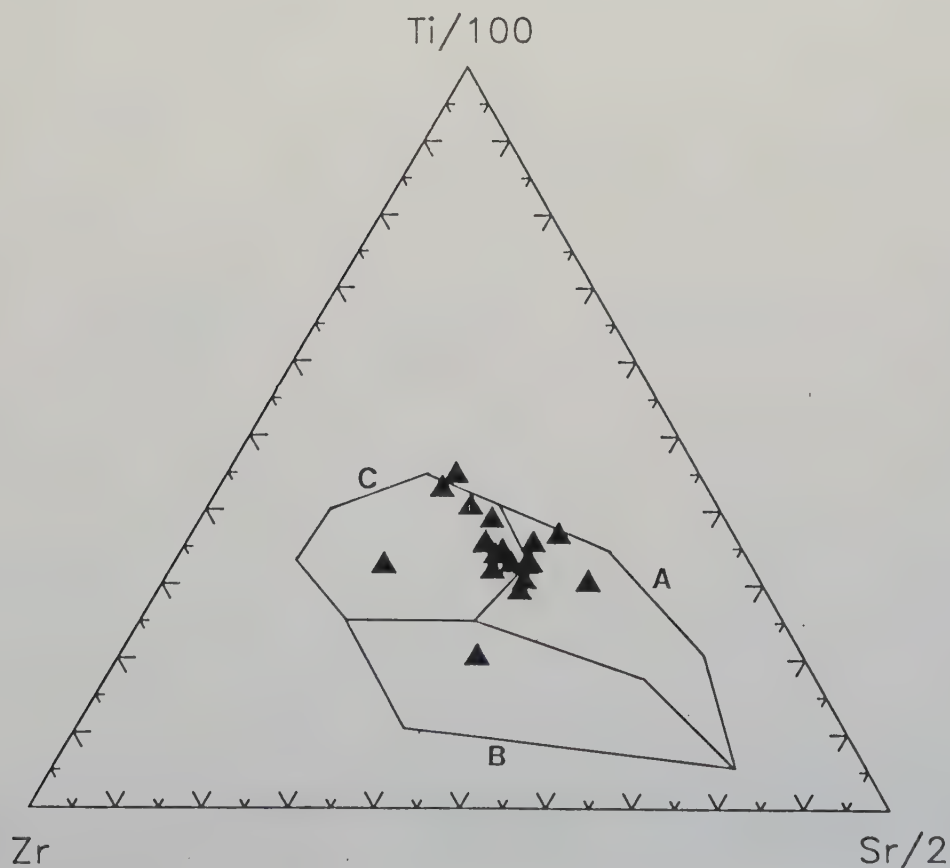


Fig. 7.4. Discrimination diagram after Pearce & Cann (1973) for Troodos glasses (triangles). Fields are: A - LKT, B - CAB, C - OFB. Abbreviations as in Fig. 7.3.

glasses fall in the low K-tholeiite fields in these diagrams (Fig. 7.3, 7.4). However, some samples lie outside the given fields or in the ocean floor basalt field, and one sample plots in the calcalkaline field. Therefore a unique discrimination is not possible with this method.

Concentrations of the LFS elements and Th in Troodos whole rocks are variable (Fig. 4.9, 4.14 - 4.16), but in the analyzed glasses they are generally lower than those found in island arc volcanics (e.g. White & Patchett, 1984, Morris & Hart, 1983), including those found in island arc tholeiites. However the importance of these elements lies not so much in their absolute abundances but rather their abundance ratios with respect to each other and the REE and high field strength (HFS) elements. The following points are significant (Table 7.3):

1. The Cs/Rb ratio in the eight Troodos glasses analyzed is 0.0413 ± 0.005 . This is substantially higher than the constant ratio observed in MORB (ca. 0.013 ± 0.0004) (Hofmann & White, 1983) but it is similar to that of island arc volcanics (White & Patchett, 1984, Morris & Hart, 1983).
2. The Ba/Rb ratio in the glasses is 5.51 ± 0.9 , lower than that found in MORB (11.4 ± 0.19) (Hofmann & White, 1983), but within the range

Table 7.3. Alkali and alkaline earth element ratios of Troodos glasses, MORB, island arc volcanics and back arc basin basalts

	Rb/K	Cs/Rb	Ba/Rb
1 Troodos	.0025±.0003	.0413±.005	5.51±0.9
2 IAV*	.0021±.0005	.0441±.0193	13.75±7.10
3 IAV*	.0020±.0002	.0427±.0122	15.14±4.00
4 Scotia Sea			10.34
5 D25	.0020		13.75
6 Ata 8-9		.0337	23.87
7 D1-5	.0020	.0225	11.83
8 N-MORB	.0005±.0002	.013 ±.0004	11.4 ±0.19

1. Troodos: all glasses
2. island arc volcanics* (White & Patchett, 1984), n=32.
3. island arc volcanics* (Morris & Hart, 1983), n=14.
4. back-arc basin basalt, average of samples 1-5, Scotia Sea (Saunders & Tarney, 1979).
5. Dredge 24, Scotia Sea (Saunders & Tarney, 1979).
6. Ata 8-9, Tonga arc (Jenner et al., 1987).
7. D1-5 andesite, Lau Basin (Jenner et al., 1987).
8. N-MORB (Hofmann & White, 1983), n=142.

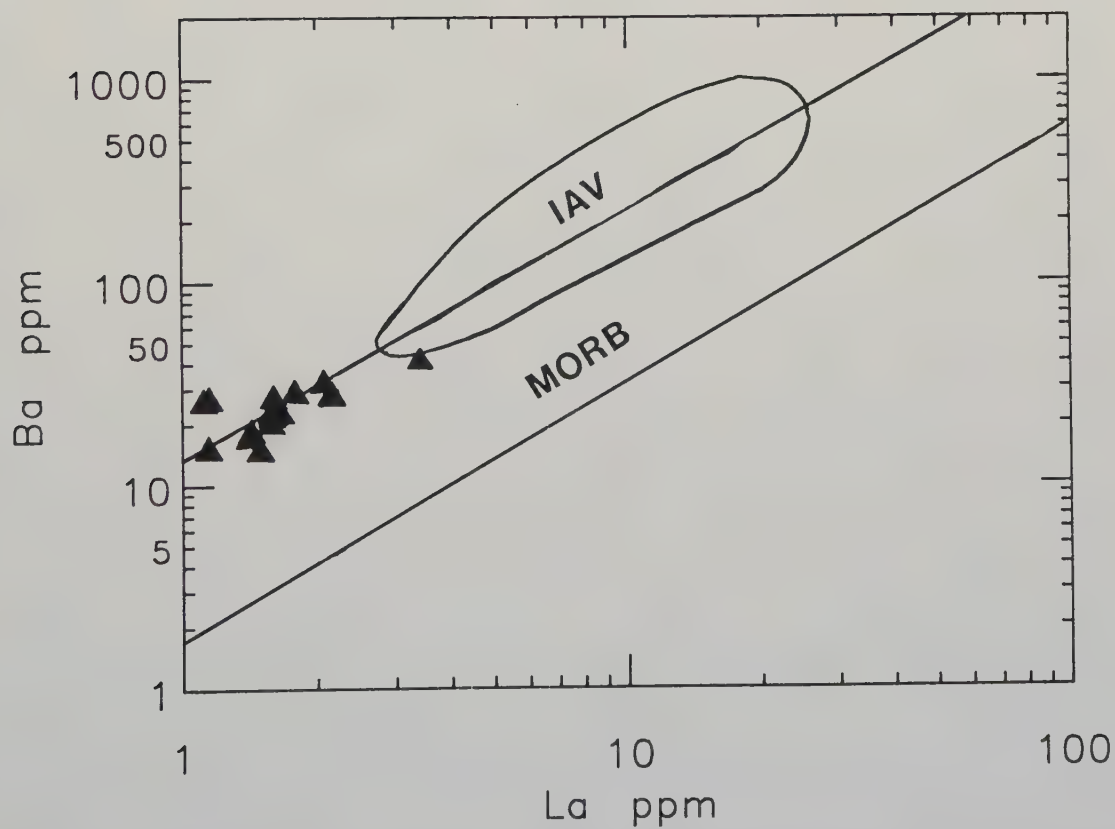
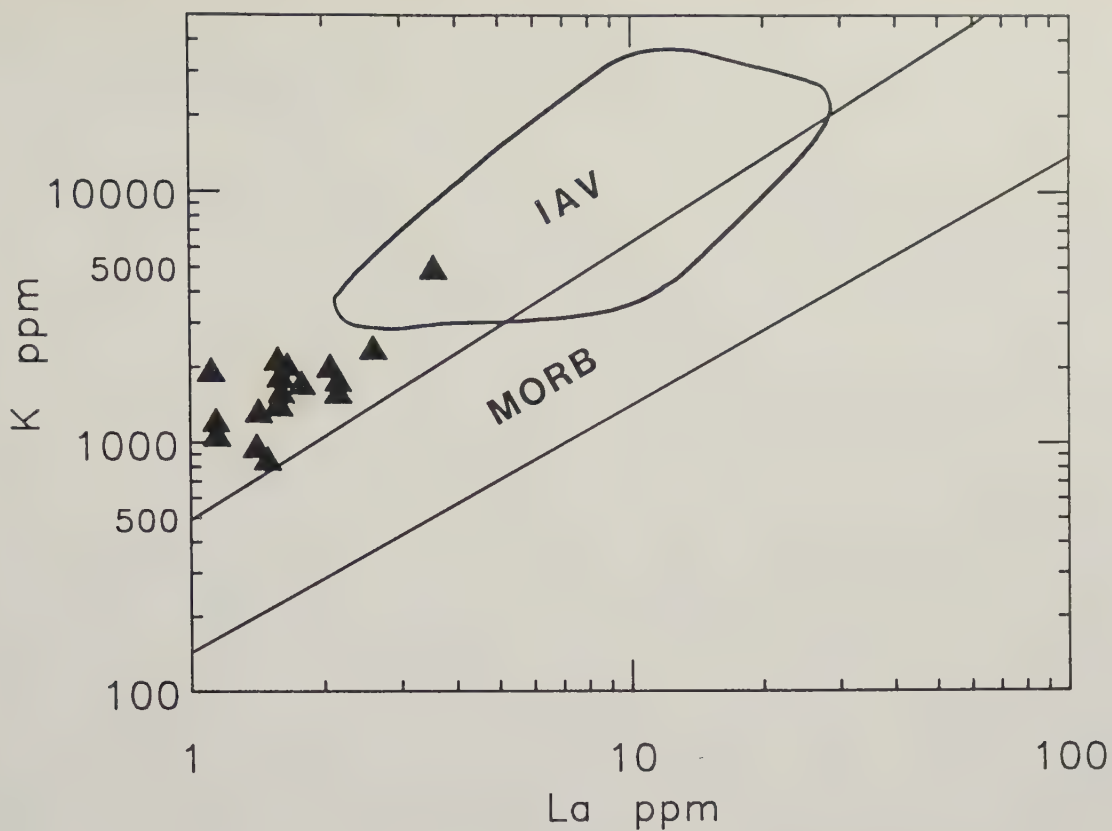


Fig. 7.5. K and Ba versus La for Troodos glasses (triangles), MORB (Hofmann & White, 1983) and island arc volcanic (IAV) fields (White & Patchett, 1984) are given.

reported from island arc volcanics (3.4 to 34.3) (White & Patchett, 1984).

3. Rb/K ratios (0.0025 ± 0.0003) in the Troodos glasses fall within the range reported for MORB and island arc volcanics.
4. All LFS elements in the glasses are overabundant relative to HFS and light REE and fall on the lower end of the trends shown by White & Patchett (1984) (Fig. 7.5).

Abundances of HFS elements are low, with values normalized to primitive mantle of less than 5 for most mafic samples. Such low abundances for HFS are characteristic for island arc volcanism (Briqueu et al., 1984; Saunders & Tarney, 1984; Pearce et al., 1984).

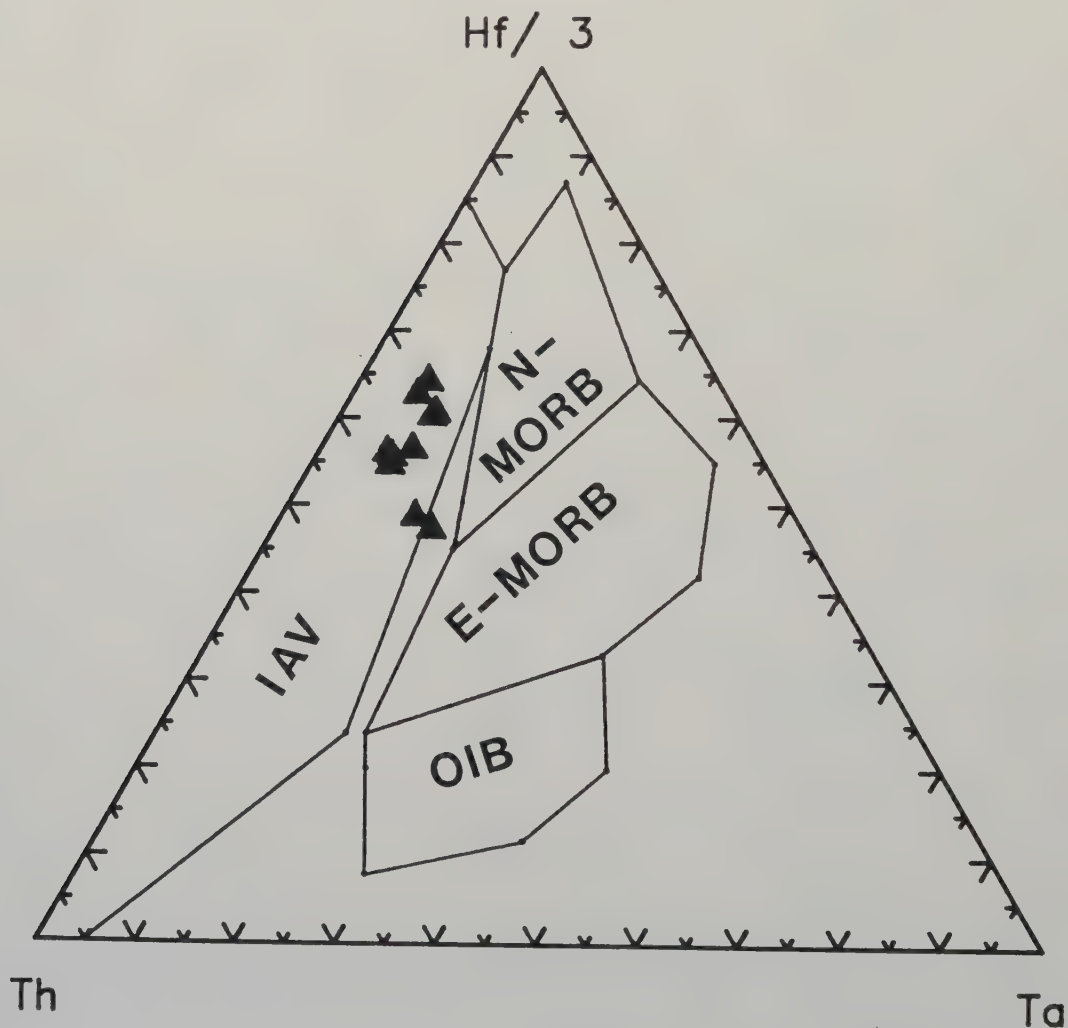


Fig. 7.6. Hf/3:Ta:Th diagram for Troodos glasses (triangles) (after Wood et al., 1979). Fields for IAV: island arc volcanics, OIB: ocean island basalt, E-MORB and N-MORB are given.

Close examination of the REE patterns in the Troodos glasses (Fig. 4.20 - 4.22) reveals that that several samples show positive La anomalies. Positive La anomalies or negative Ce anomalies are common in island arc volcanics (White & Patchett, 1984). As a result of insufficient data base it is not yet clear if they are restricted to this group of supra-subduction zone volcanics.

Table 7.4. Trace element characteristics of averages of mafic Troodos glasses, BAB, IAT, N-MORB, and normalizing values for primitive mantle.

	1 Troodos low high		2 IAT Sun	3 Scotia Sea	4 D.24	5 Ata 8-9	6 D1-5 Lau	7 N-MORB	8 Prima
K	836	1656	3240	1552	1992	5180	4320	955	.636
Rb	1.85	5.36	4.6	5.75	4	8	8.62	1.12	.504
Cs	.058	.238	.22	-	-	.27	.194	.0131	.00636
Sr	68.44	98.14	200	221	123	268	169	122	17.6
Ba	14.16	22.14	110	61	55	191	102	14.3	5.7
Th	.20	.25	.25	-	-	-	-	.185	.0754
Nb	.3	1.4	.7	4	1	-	-	3.58	.78
Ta	.039	.071	.044	.80	.36	-	-	.158	.0364
Hf	.77	1.23	-	-	-	1.19	-	2.87	.312
Zr	22	37	22	104	40	47	-	100	9.93
Y	14	22	12	27	14	19	-	34.2	3.74
Ti	2697	4496	3000	7253	3656	4496	-	8692	-
La	.878	1.604	1.3	5.58	2.57	3.86	4.35	3.96	.636
Ce	2.394	4.867	3.7	12.48	6.45	9.72	12.27	11.97	1.66
Nd	2.431	4.666	3.4	10.04	4.55	7.84	10.73	10.96	1.23
Sm	1.026	1.735	1.2	3.03	1.46	2.42	3.59	3.62	.400
Eu	.419	.701	-	1.12	.56	.87	1.31	1.31	.151
Gd	1.625	2.553	1.55	3.49	1.99	-	4.83	4.78	.531
Dy	2.155	3.247	1.95	4.28	2.38	3.23	5.80	5.98	.661
Er	1.440	2.084	1.28	2.75	1.58	2.04	3.85	3.99	.432
Yb	1.435	2.057	1.25	2.66	1.59	1.65	3.75	3.73	.429
Lu	.217	.320	-	-	-	.34	.577	.561	.066

1. Troodos glasses: highest and lowest values from range of samples 305, 316, 331, 340, 345, 350, 371, and 544.
2. island arc tholeiite (Sun, 1980).
3. back-arc basin basalt, average of samples 1-5, Scotia Sea (Saunders & Tarney, 1979).
4. Dredge 24, Scotia Sea (Saunders & Tarney, 1979).
5. Ata 8-9, Tonga arc (Jenner et al., 1987).
6. D1-5 andesite, Lau Basin (Jenner et al., 1987).
7. N-MORB (Hofmann & White, 1983, Jochum et al., 1983, 1986, Hofmann et al., in prep).
8. normalizing values for primitive mantle (Jochum et al., 1986, Hofmann et al., in prep.).

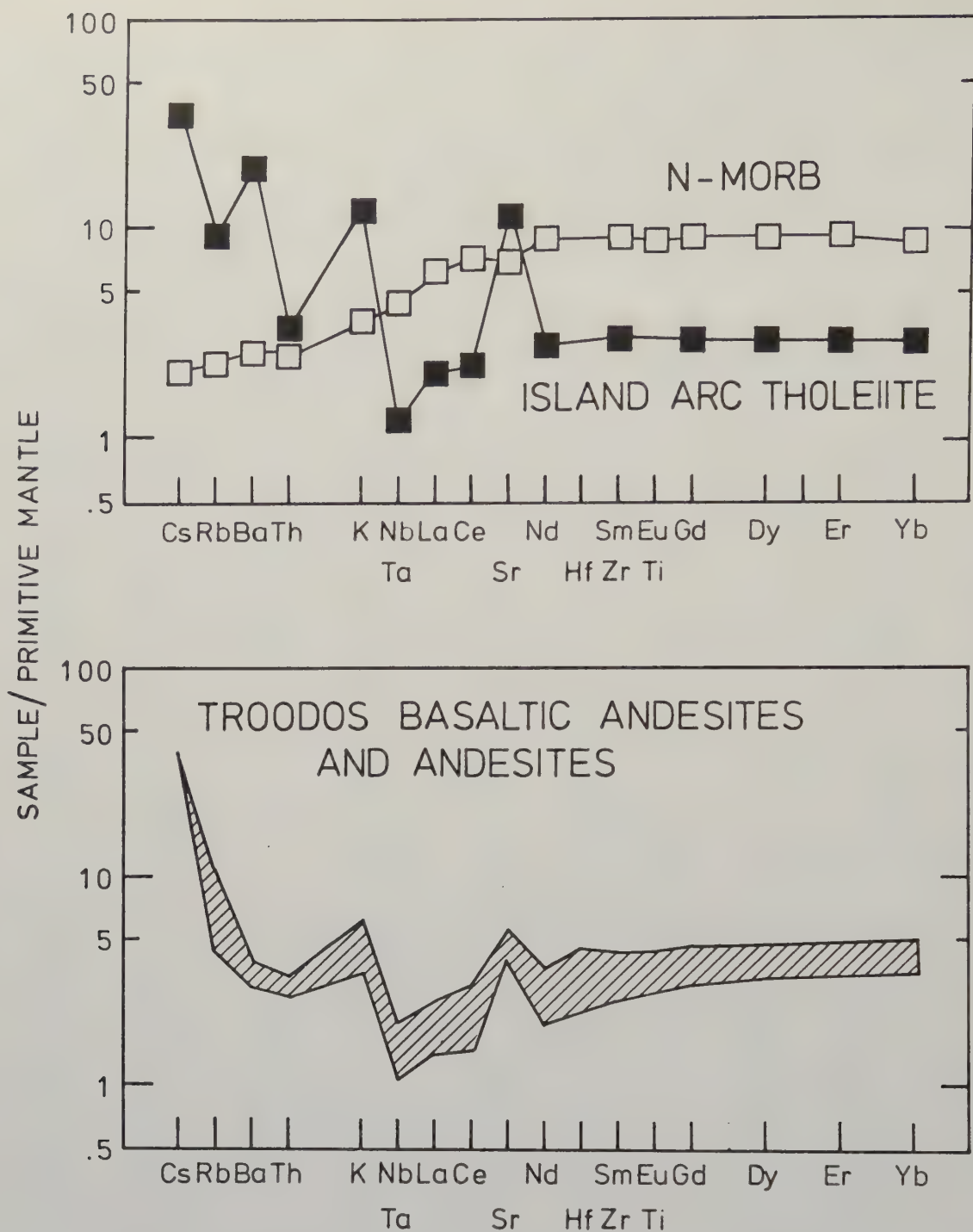


Fig. 7.7. Trace element abundances of mafic Troodos glasses, normalized to primitive mantle (normalizing values are given in Table 7.4). Averages of island arc tholeiite from Sun (1980), and N-MORB (Hofmann et al., in prep.). The pattern of Troodos glasses is similar to that of island arc tholeiite, but is distinct from that of N-MORB.

Troodos glasses have low Nb and Ta concentrations relative to HFS elements and thus fall in the volcanic arc basalt field on a Hf/3:Ta:Th discrimination plot (Fig. 7.6) (Wood et al., 1979). The results overlap with results reported from Troodos whole rock analyses (Pearce et al., 1984). They are comparable with those of the Palau-Kyushu remnant arc (Wood et al., 1980b).

The average trace element composition of the mafic Troodos glasses is compared with corresponding averages of N-MORB and island arc tholeiites in Fig. 7.7 (Table 7.4). N-MORB are characterized by an increasing depletion with increasing incompatibility (from right to left) producing a smooth pattern. In contrast to this, island arc tholeiites and many marginal basin basalts show an irregular pattern, characterized by higher abundances of LFS elements relative to the REE. Other distinct characteristics of island arc tholeiites and other

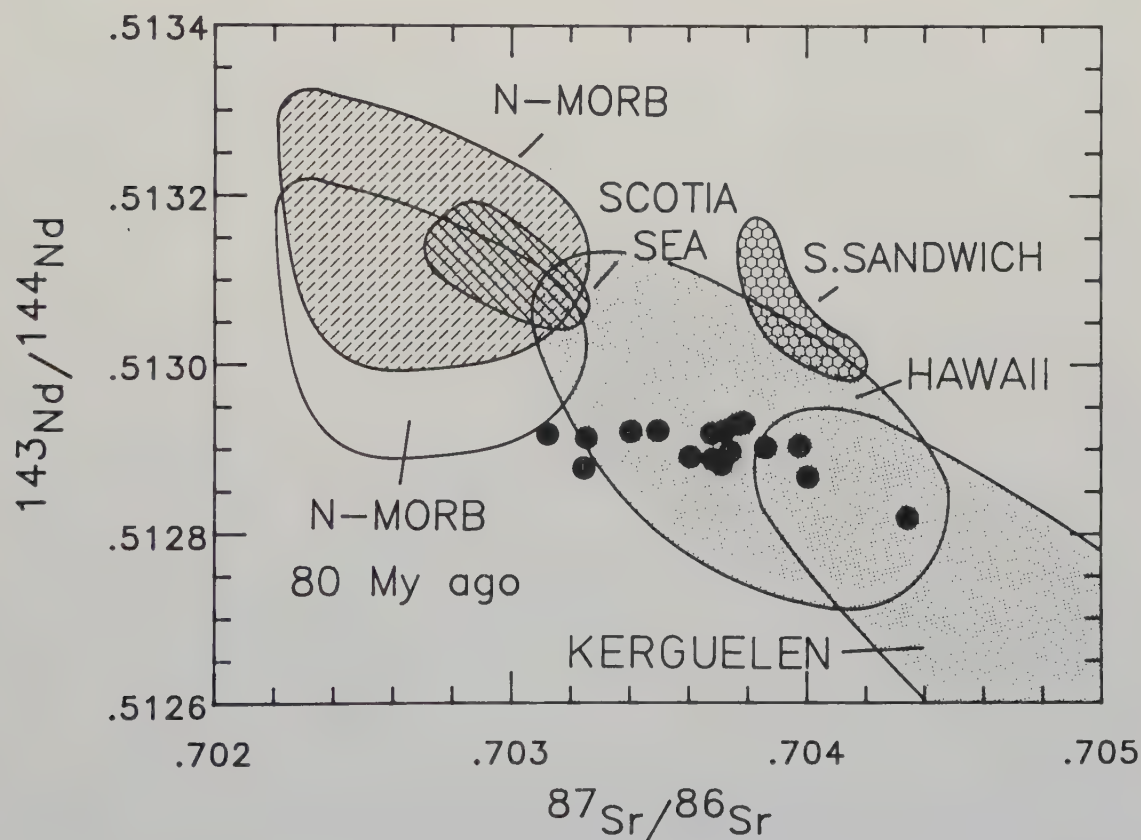


Fig. 7.8. Sr-Nd isotopic variations for Troodos glasses (dots) and the mantle array, defined by N-MORB, Hawaii and Kerguelen, Scotia Sea back arc basin, South Sandwich island arc. Data sources are White & Hofmann (1982), Cohen & O'Nions (1982a,b), Jenner et al. (1985), Hawkesworth et al. (1977). The open field for N-MORB has been age-corrected for 80 My in the same way as the Troodos glasses.

island arc volcanics are an underabundance of Ta and Nb relative to the REE (Sun, 1980, Briquieu et al., 1984, Saunders & Tarney, 1984) and generally lower absolute abundances of REE. In general, marginal basin basalts do not have well developed Ta-Nb anomalies (Saunders & Tarney, 1984), though exceptions are found in Dredge 24 samples from the Scotia Sea (Saunders & Tarney, 1984) and some basalts in Holes 454A and 456A in the Mariana Trough (Natland & Tarney, 1981). Lau basin andesites of the Valu Fa ridge show Nb depletions relative to the REE (Vallier et al., submitted).

7.5 ISOTOPIC COMPOSITION

Sr and Nd isotopic compositions of the Troodos glasses are shown in Fig. 7.8. To facilitate a comparison of the 80 Ma old Troodos rocks with those of modern volcanics, the present day "mantle array" (defined by N-MORB, Hawaii and Kerguelen) was "age"-corrected for the decay of ^{147}Sm and ^{87}Rb . The shift in Sr isotopic composition for the N-MORB field is insignificant, because the Rb concentration in N-MORB is very low. The Troodos glasses lie at the low end of the age-corrected N-MORB field and show a trend of enrichment of radiogenic Sr compared with Nd. Recent island arc volcanics have both low Nd and high Sr isotopic composition compared with N-MORB today (White & Patchett, 1984).

The Pb isotopic composition of the Troodos glasses is shown in comparison with those for island arc, back-arc and N-MORB volcanics in Fig. 7.9 - 7.10. The Troodos glasses plot close to or slightly above the field for N-MORB. An important characteristic of island arc and some back-arc volcanics is their trend off the N-MORB array towards pelagic sediment. As can be seen in Fig. 7.9 - 7.10, the Troodos glasses show a similar trend. Hamelin et al. (1984) also report high $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ ratios for gabbros and sheeted dike rocks from the Troodos ophiolite.

In summary, the major and trace element chemistry and isotopic composition of the Troodos samples closely resembles that shown by island arc tholeiites. The similarities include LREE-depleted REE patterns with low absolute abundances of REE, negative Ta and Nb anomalies and positive anomalies of the alkali and alkaline earth metals, low Nd, and high Sr and Pb isotopic compositions relative to N-

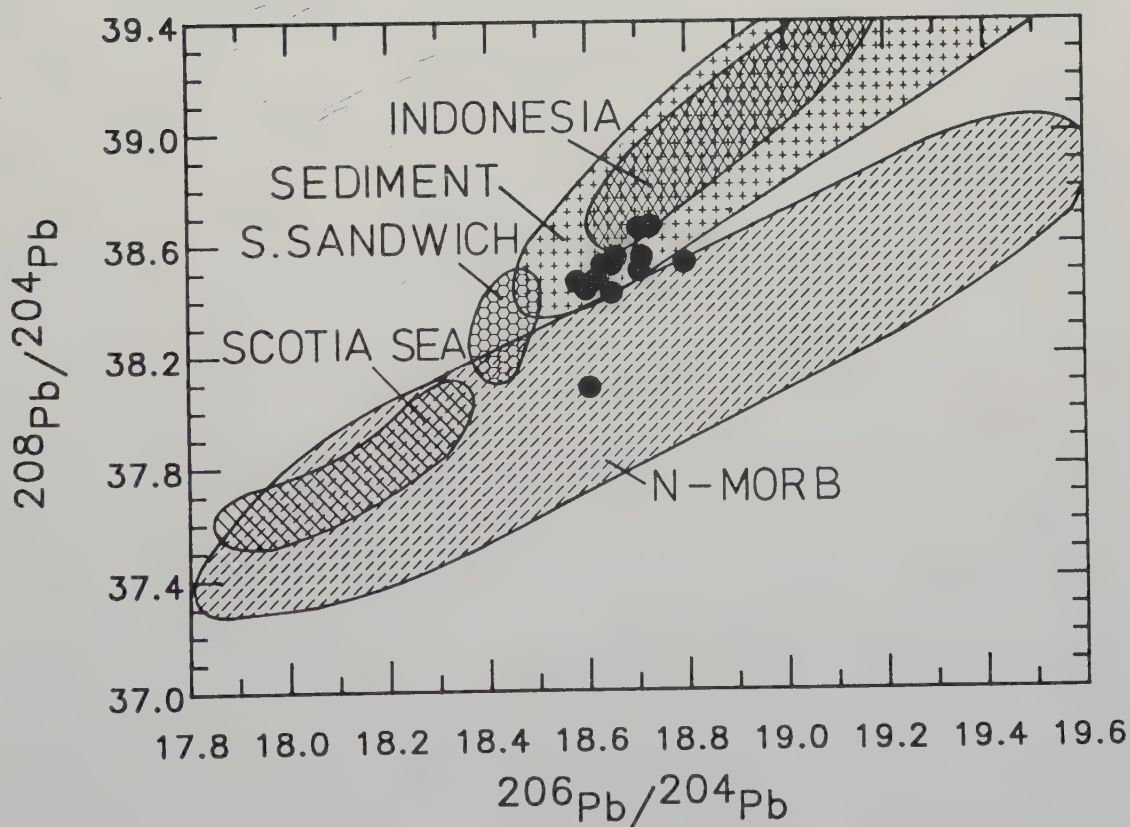
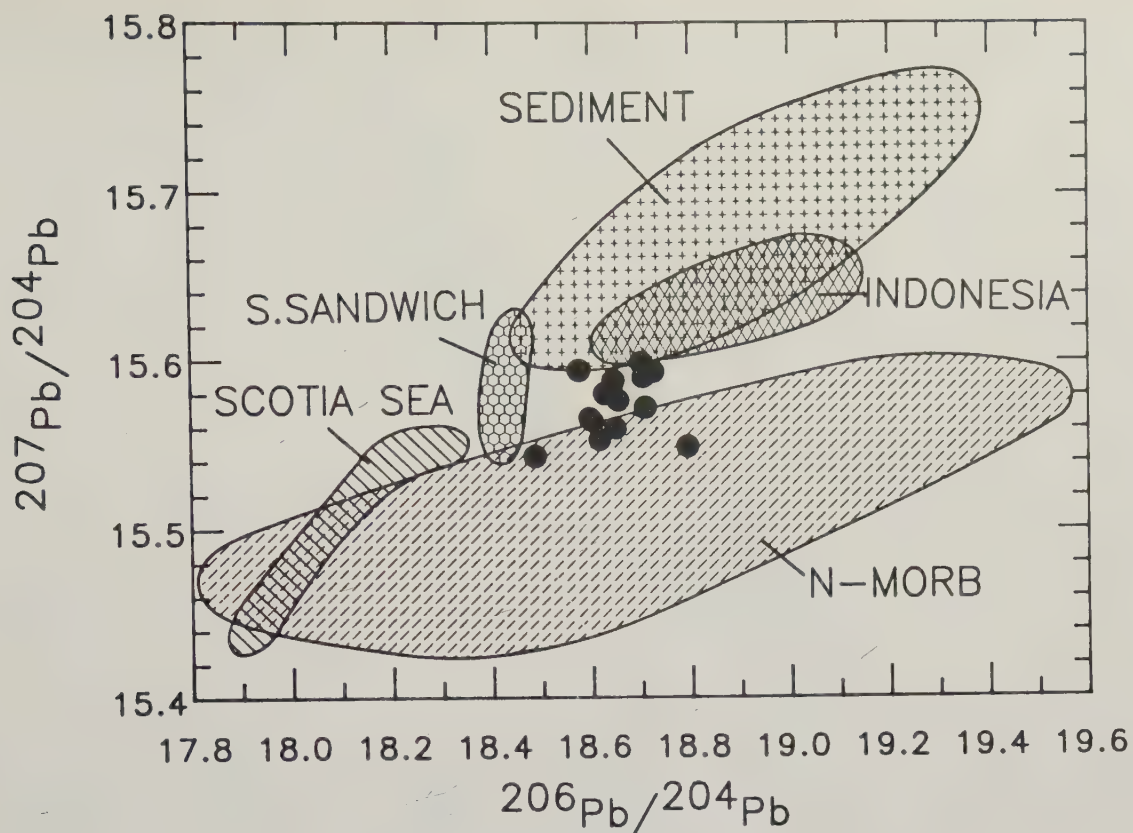


Fig. 7.9. Pb-Pb isotopic compositions for Troodos glasses (dots), Scotia Sea back arc basin, South Sandwich island arc, Indonesian island arc, and oceanic sediments. Data sources are as in Fig. 7.8, and White (1985), Jenner et al. (unpubl.), Barreiro (1983).

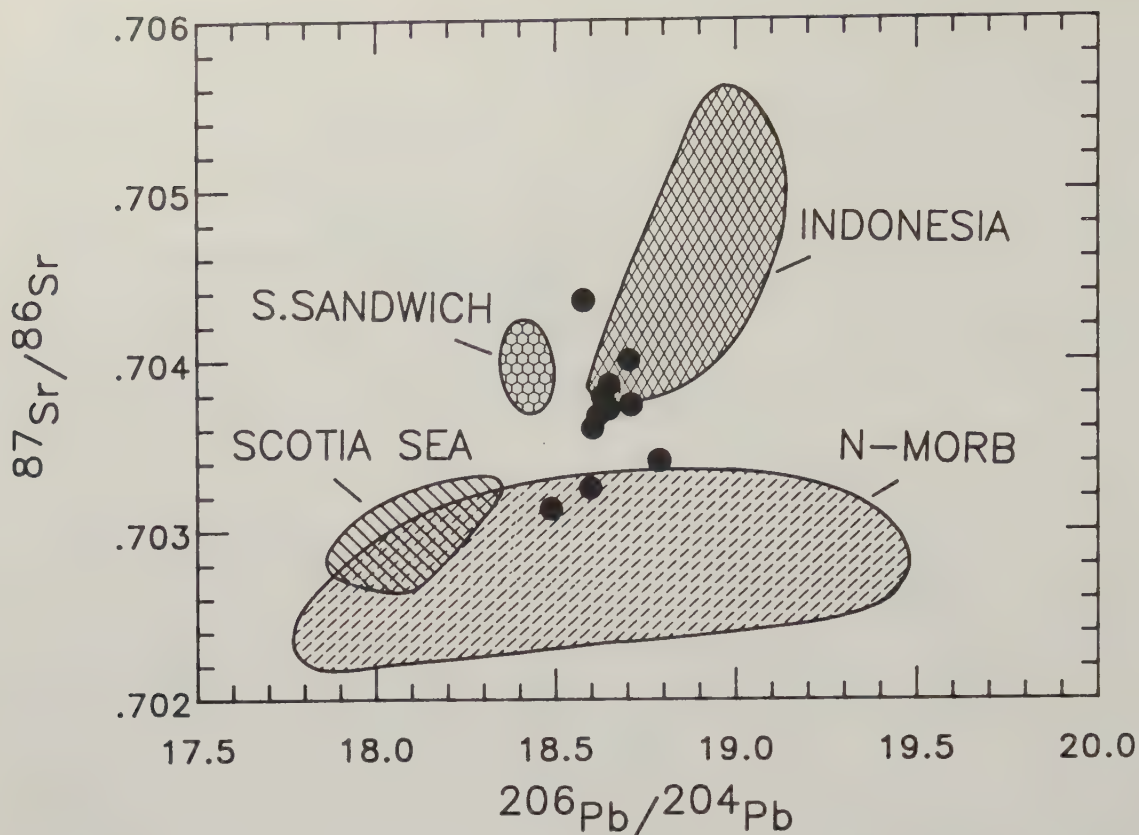


Fig. 7.10. Sr-Pb isotopic compositions for Troodos glasses (dots), Scotia Sea back arc basin, South Sandwich island arc, and Indonesian island arc. Data sources are as in Fig. 7.9.

MORB. Considering the chemical composition of the rocks, a major ocean spreading ridge for Troodos seems unlikely.

7.6 BACK-ARC OR ISLAND ARC ORIGIN?

It is difficult to distinguish between back arc and island arc origin on purely geochemical grounds, in part because there are still few data on back arc basin rocks. The occurrence of volcanics with characteristics similar to those of Troodos has been described mostly from typical island arc tholeiites (e.g. Tonga, Fiji, Mariana arc) and in some cases also from back-arc basins (Dredge 24, Scotia Sea back-arc basin (Saunders & Tarney, 1979, 1984), Mariana Trough, Holes 454A. 456A (Natland & Tarney, 1981) and the Lau Basin (Jenner et al., 1987, Vallier et al., submitted)).

An origin in a back arc basin has mainly been proposed because of the presence of a sheeted dike swarm in the Troodos ophiolite (Kidd &

Cann, 1974). This was interpreted as an indication of sea floor spreading at the time of formation, and followed by the interpretation that the ophiolite formed at a spreading axis in an ocean basin. However, spreading may also occur in an island arc setting, where extensional regimes are common (Leitch, 1984). Thus, the presence of a sheeted dike complex in the ophiolite does not necessarily indicate a formation at a spreading axis.

Several lines of evidence suggest that the Troodos ophiolite represents oceanic crust formed in the earliest stages of island arc development (as also discussed by Pearce et al. 1984), rather than formation in a back-arc basin. The important points are:

1. Some back-arc basalts may show several of the characteristics of primitive island arc lavas, such as enrichment in LFS relative to REE and HFS elements, and negative Ta-Nb anomalies (Natland & Tarney, 1981, Saunders & Tarney, 1984, Jenner et al., 1987, Vallier et al., submitted). These back-arc basin basalts have either LREE-enriched REE patterns, as in the case of Dredge 24 of the Scotia Sea (Saunders & Tarney, 1979), or they occur together with N-MORB basalts, as in the Mariana Trough (Wood et al., 1980b) and in the Lau Basin (Gill, 1976, Hawkins, 1976, Hawkins, 1977, Hawkins & Melchior, 1985, Jenner et al., 1987, Vallier et al., submitted). However, Troodos volcanics have the enrichment in LFS relative to REE and HFS, but are neither LREE enriched, nor do they occur together with N-MORB or MORB (Miyashiro, 1973, Smewing et al., 1975, Robinson et al., 1983, Schmincke et al., 1983, Pearce et al., 1984, Rautenschlein et al., 1985).

2. High-SiO₂, high-MgO volcanics with similarities to Bonin Island, Mariana Trench and Cape Vogel volcanics (Dietrich et al., 1978, Jenner, 1981, Saunders & Tarney, 1984) occur in the Troodos complex (McCulloch & Cameron, 1983, Cameron, 1985). Whereas the tectonic setting of this type of volcanism at the time of origin is debated (Crawford et al., 1981, Wood et al., 1981, Pearce et al., 1984), there is consensus that these magmas formed shortly after or during the initiation of subduction (Natland & Tarney, 1981, Pearce et al., 1984). They have not yet been reported from back-arc basins.

3. There is no geologic evidence that the environment within which the

Troodos ophiolite formed was associated with a well developed island arc (Pearce et al., 1984, Moores et al., 1984). One of the arguments is the absence of pyroclastic rocks within the volcanic sequence. Moores et al. (1984) have presented a back-arc model based on the Andaman Sea for Troodos, where spreading occurs above a subduction zone without the presence of a well developed island arc. They argue that this model can account for the geologic and geochemical features of the Troodos ophiolite. This model may not be able to account for the geochemistry of the Troodos volcanics, because, considering the data available, in present-day back-arc basins, the occurrence of differentiated suites of volcanics and/or back-arc basin basalts with negative Ta-Nb anomalies (chemical compositions similar to those of Troodos glasses) appears restricted to basins formed behind a well developed island arc (Saunders & Tarney, 1984). However, no evidence for an island arc is present.

7.7 CONCLUSIONS

The major and trace element chemistry and isotopic composition of the Troodos samples closely resembles that shown by island arc tholeiites. The similarities include LREE-depleted REE patterns with low absolute abundances of REE, negative Ta and Nb anomalies and positive anomalies of the alkali and alkaline earth metals, low Nd, and high Sr and Pb isotopic compositions relative to N-MORB. Considering the chemical composition of the rocks, a major ocean spreading ridge for Troodos seems unlikely.

The discrimination between subduction-zone related volcanics, originated in back arc basins and island arcs is difficult to accomplish by using only chemical composition because of the small data base for back arc basin volcanics. Considering that there is no evidence for a well-developed island arc, an origin of the Troodos ophiolite in an early stage of island arc evolution seems more plausible than the formation in a back arc basin.

CHAPTER 8. MANTLE SOURCES AND MAGMA GENESIS

8.1 INTRODUCTION

Troodos volcanics cover a range of compositions, but only mafic lavas will be considered. At MgO contents between 7 and 9%, the glass data show a significant spread in major and trace element concentrations and isotopic compositions. For example, SiO₂ concentrations range from 53.1 to 56.3%, TiO₂ from 0.45 to 0.75%, and HREE from 6.5 to 9.4 x chondritic (Fig. 4.2, 4.3, 4.20). The mafic glasses cover the whole range of variation in Sr, Nd, and Pb isotopic compositions, and the isotopic compositions are not correlated with the degree of differentiation (Fig 8.1, 8.2).

Several processes that operate during the generation and fractionation of magmas may generate such differences in composition:

1. secondary alteration
2. fractional crystallization / crystal accumulation
3. differences in the degree of partial melting
4. mixing with other components before or after magma generation
5. heterogeneity in the magma source

Secondary alteration has been treated earlier (Chapter 5). This led to the conclusion that the Troodos glasses are fresh and represent original compositions. For whole rocks, only those element concentrations and isotopic ratios that are not affected by secondary alteration processes will be considered.

The fractionation of isotopic compositions in fractional crystallization and partial melting processes is mass-dependent. Isotopes of elements with small masses, such as ¹⁸O and ¹⁶O can be fractionated during these processes, because the difference between the masses of these isotopes is relatively large. This effect is small for the elements Sr, Nd and Pb, where differences in mass between the isotopes are relatively small. The isotopes of these elements are therefore considered not to be fractionated during partial melting or fractional crystallization processes. The isotopic compositions of these partly radiogenic elements is only changed by a change in the parent/daughter element ratio and subsequent radioactive decay with time. Thus, heterogeneous isotopic compositions of Sr, Nd, and Pb

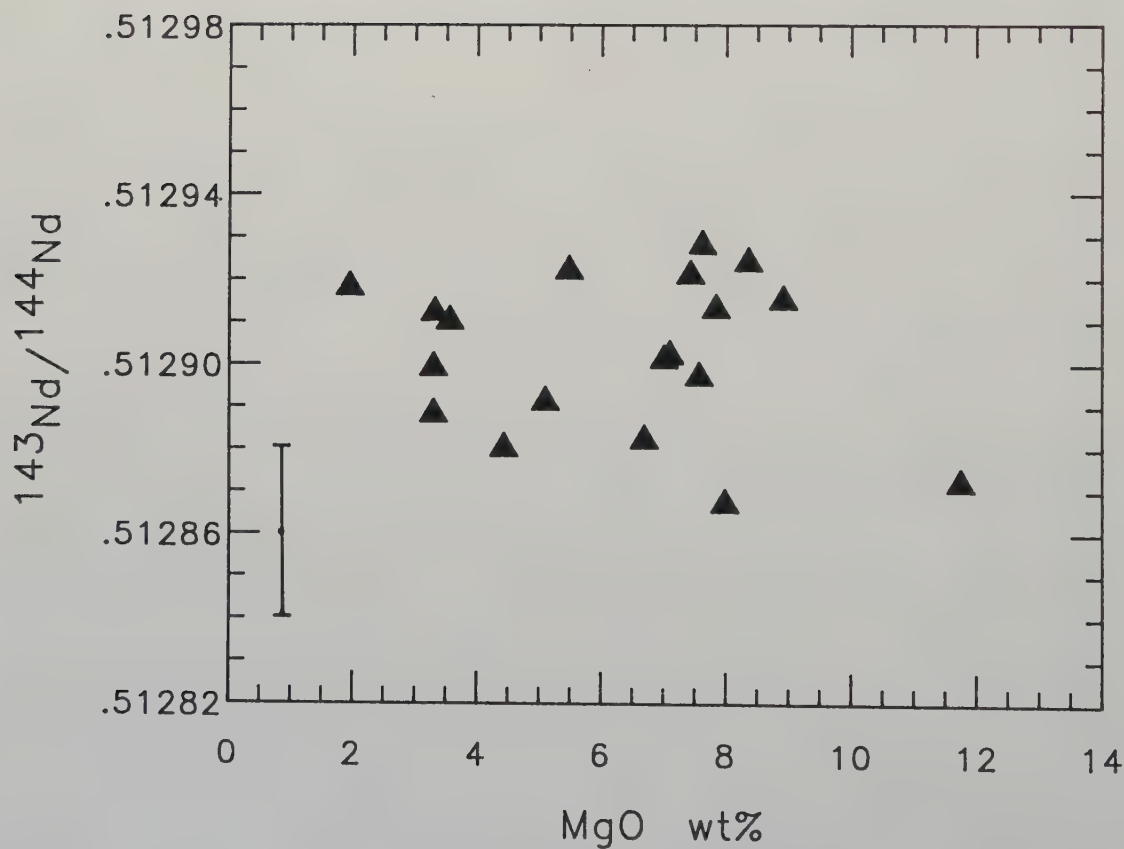
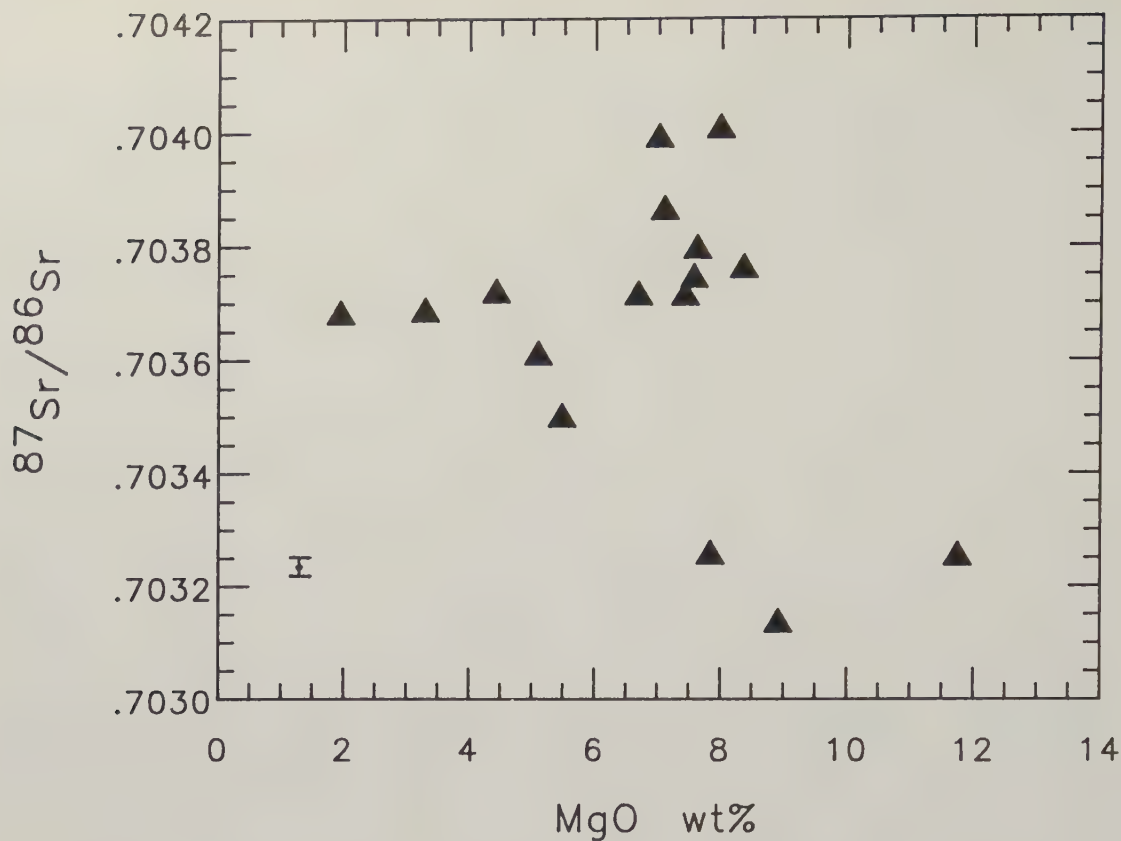
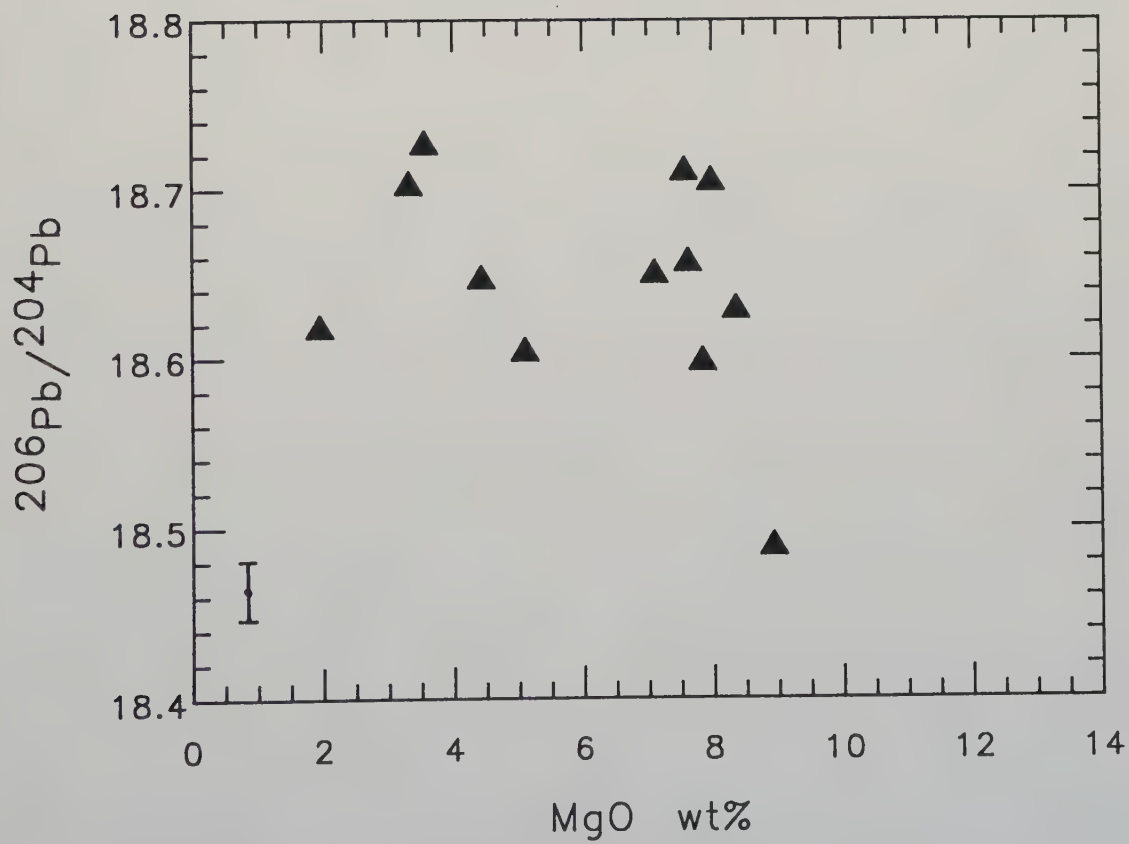
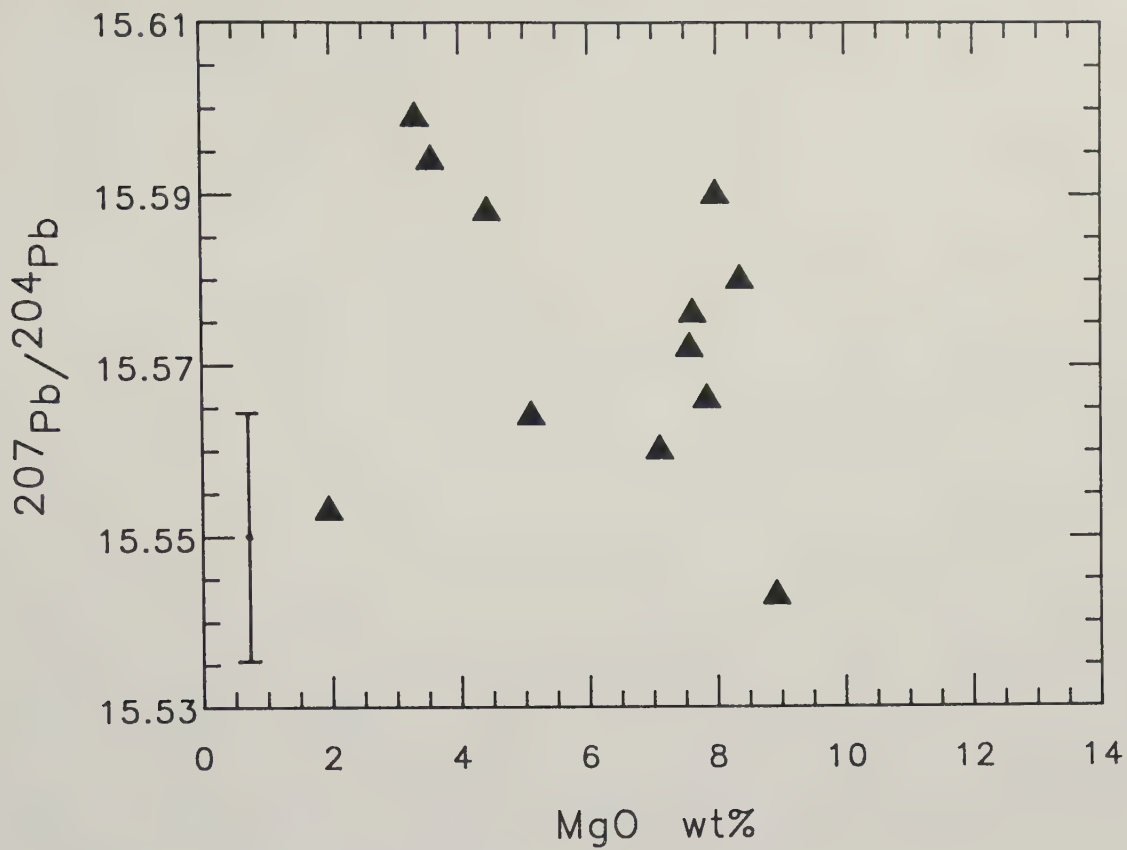


Fig. 8.1. MgO versus $\text{Sr}^{87}/\text{Sr}^{86}$ and $\text{Nd}^{143}/\text{Nd}^{144}$ initial ratios for Troodos glasses (triangles). Error bars are shown.



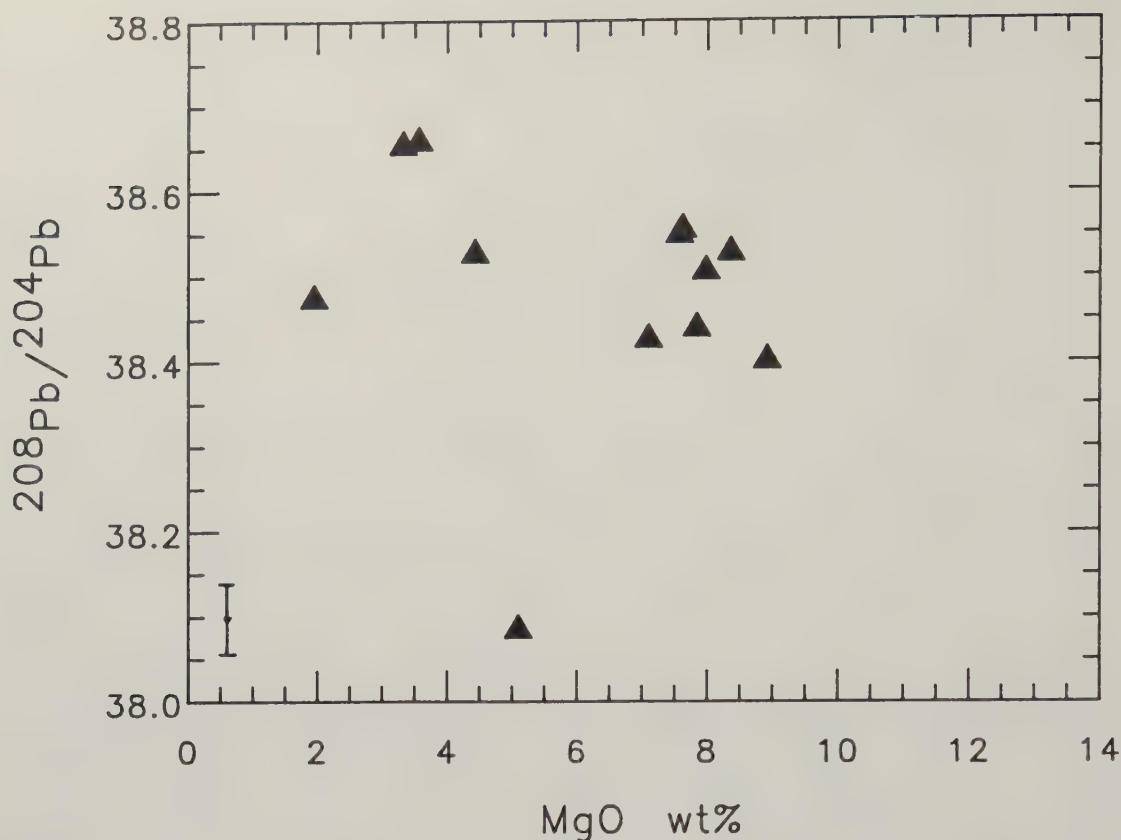


Fig. 8.2. MgO versus $\text{Pb}^{206}/\text{Pb}^{204}$, $\text{Pb}^{207}/\text{Pb}^{204}$, $\text{Pb}^{208}/\text{Pb}^{204}$ for Troodos glasses (triangles). Error bars are given.

suggest that partial melting and fractional crystallization cannot be the only processes operating in the generation of Troodos magmas. The lavas show a significant variation in isotopic composition indicating heterogeneities in the mantle source and/or mixing of components with different isotopic characteristics during magma generation or ascent.

This chapter will demonstrate that the relationships of the major element compositions between different samples are consistent with fairly large degrees of fractional crystallization, but when these degree of crystal fractionation are applied to the trace elements, large discrepancies are obtained. A large part of these discrepancies may be explained simply by differences in the degree of melting of different primary magmas, but even this does not account for the isotopic differences and the differences in Ba/Rb. Consequently, the source(s) of the primary melts must be heterogeneous. Most of this heterogeneity can be explained by mixing of variably depleted mantle

and pelagic sediment prior to partial melting. However, this does not account for the variation in Sr isotopic ratios and Ba/Rb ratios. This requires a further component in the mantle source, namely an incompatible-element-rich fluid phase.

8.2 FRACTIONAL CRYSTALLIZATION

The analyzed glasses and whole rocks are almost aphyric, suggesting crystal accumulation has not affected their chemical composition. Therefore, only fractional crystallization will be considered. Petrographic observations suggest several mineral phases have fractionated the composition of the magmas: olivine, clinopyroxene, orthopyroxene, plagioclase, and opaques (Chapter 3). The mineral phases have been analyzed for major element composition by microprobe. Typical compositions are given in Table 8.1. Major and trace element compositions of glasses and mineral phases are used to constrain the choice and the amount of minerals which have fractionated the Troodos magmas. After a qualitative discussion selected examples will be modelled quantitatively.

Table 8.1. Mineral compositions used for modelling of fractional crystallization.

	1	2	3	4	5	6	7	8
	ol	cpx	opx	plag	343	316	345	370
	av.		av.	av.				
SiO ₂	39.64	52.18	52.53	49.50	50.66	53.36	56.01	59.89
TiO ₂	-	.19	.21	-	.67	.71	.45	1.10
Al ₂ O ₃	-	3.75	1.34	31.50	14.62	15.81	14.20	13.76
FeO*	14.59	4.57	19.94	.48	7.54	7.49	7.79	10.78
MgO	45.13	17.18	24.08	.22	11.75	7.84	7.98	3.30
CaO	.19	21.22	1.78	15.67	13.21	12.42	11.24	7.73
Na ₂ O	-	.18	.08	2.60	1.15	2.05	1.86	2.79
K ₂ O	-	-	-	-	.19	.11	.20	.24
total	99.55	94.27	99.96	99.97	99.79	99.79	99.73	99.59

1. olivine, average of 7.

2. clinopyroxene, sample 544.2.

3. orthoproxene, sample 498

4. plagioclase, average of 10

5. sample 343

6. sample 316

7. sample 345

8. sample 370

The glass compositions form a trend in a Al₂O₃-CaO-MgO diagram (Fig. 8.3a). Arrows indicate the effect of fractional crystallization for individual mineral phases. In the case when olivine or

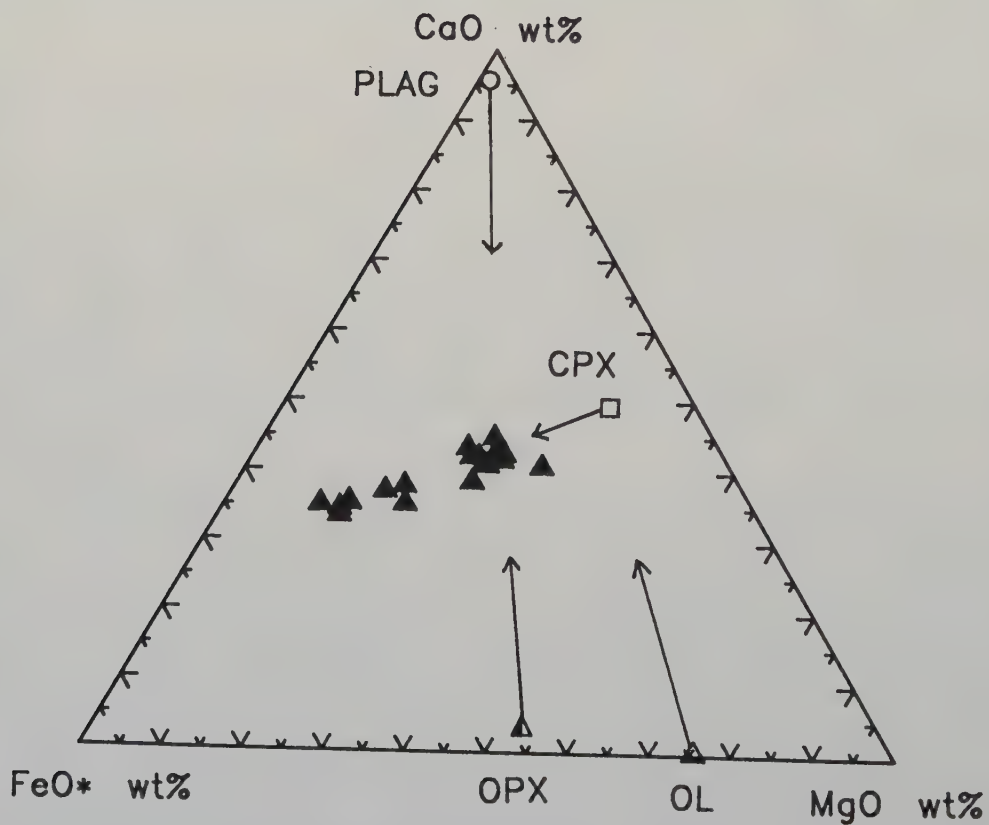
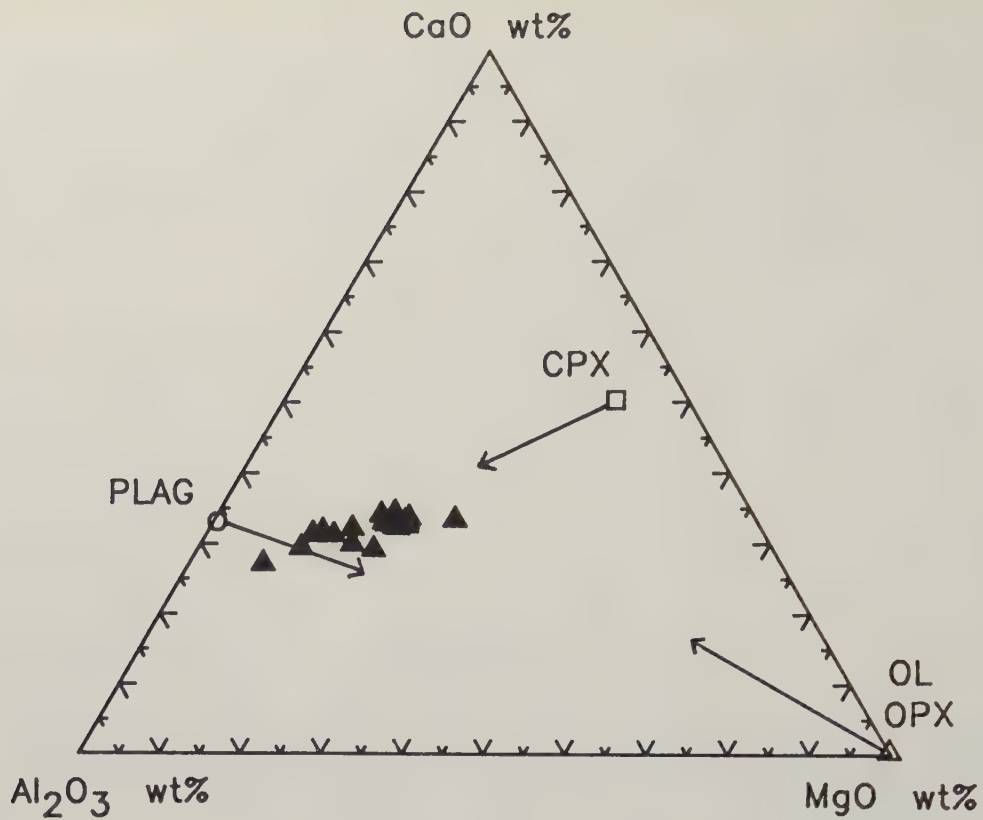


Fig. 8.3. Al_2O_3 - CaO - MgO and FeO^* - CaO - MgO diagrams for Troodos glasses (solid triangles) and average mineral compositions (Table 8.1). Arrows indicate fractionation trends for each mineral.

orthopyroxene are the only mineral phases fractionating (they cannot be distinguished on this diagram), only the MgO content of the lavas will decrease, whereas the ratio of CaO/Al₂O₃ will remain constant, because these minerals consist mainly of SiO₂, FeO and MgO. Fractional crystallization of plagioclase alone would result in an increase of MgO and a decrease of CaO and Al₂O₃ in the lavas, as is indicated by the arrow on Fig. 8.3a. Because of its high MgO and CaO content, clinopyroxene fractionation would lower the MgO concentration as well as the CaO/Al₂O₃ ratio in the residual melt.

The glass compositions also form a trend in a FeO*-CaO-MgO diagram. Again, olivine and orthopyroxene would decrease MgO and FeO contents and increase CaO contents in the lavas as indicated by the arrows in Fig. 8.3b. Plagioclase fractionation would result in an opposite trend on this diagram, because it would decrease CaO but increase FeO and MgO without changing the FeO/MgO ratio. Clinopyroxene fractionation would result in a decrease in CaO/Al₂O₃ and in MgO, just as is observed in the glass trend. These diagrams suggest that clinopyroxene was an important fractionating phase, and olivine and possibly orthopyroxene had a small influence.

Fig. 8.4 shows MgO versus Al₂O₃ for the glasses. Arrows indicate the effects of fractional crystallization of each mineral phase. If only clinopyroxene and olivine or orthopyroxene were fractionating, the Al₂O₃ content of the lavas should increase with decreasing MgO, however, this is not the case. Plagioclase fractionation reduces the Al₂O₃ content and increases the MgO content in the lavas. This precludes that only olivine, clinopyroxene and orthopyroxene are fractionating phases, but plagioclase is required as well.

Some trace elements can be used as indicators for the fractionation of certain minerals, because they are compatible for only one mineral, but incompatible for others.

Fig. 8.5 shows MgO versus Ni for Troodos glasses, and an arrow towards olivine composition. Ni is compatible with respect to olivine, but less compatible with respect to clinopyroxene and incompatible with respect to plagioclase (see Table 8.2). Ni concentrations in the glasses decrease with decreasing MgO, supporting the presence of

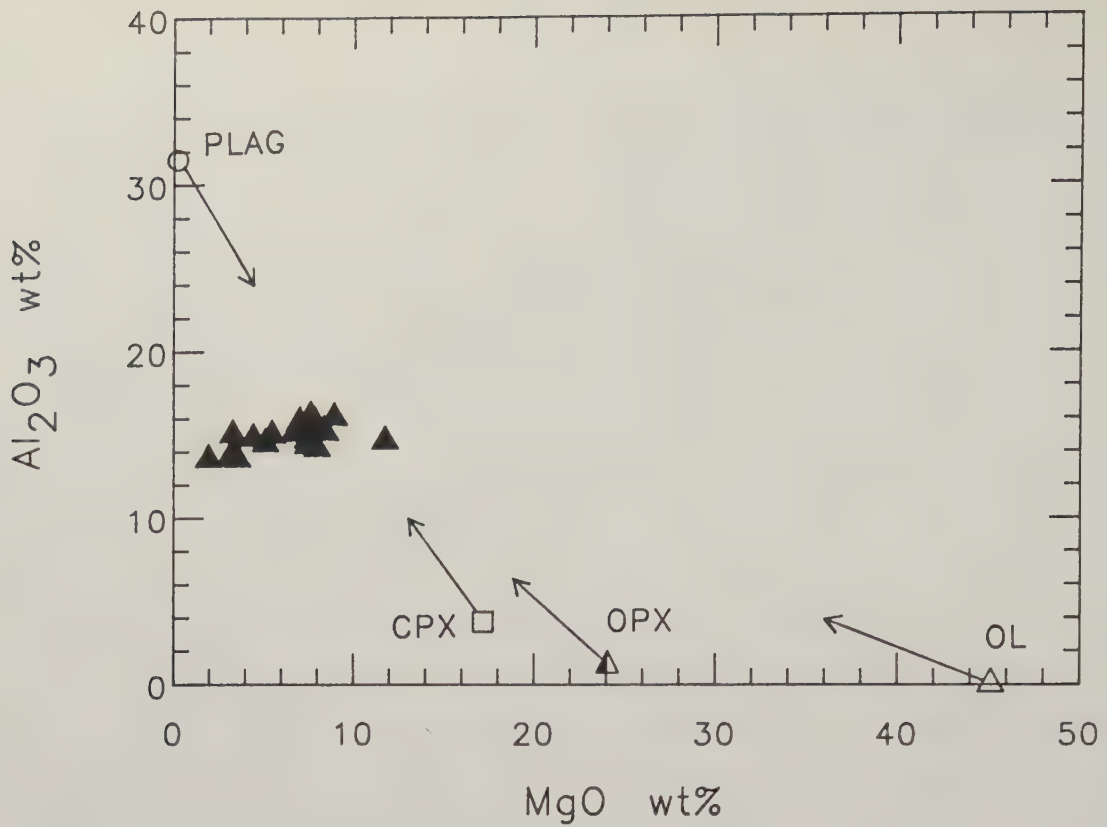


Fig. 8.4. MgO versus Al_2O_3 for Troodos glasses (solid triangles) and average mineral compositions (Table 8.1). Arrows indicate fractionation trends for each mineral.

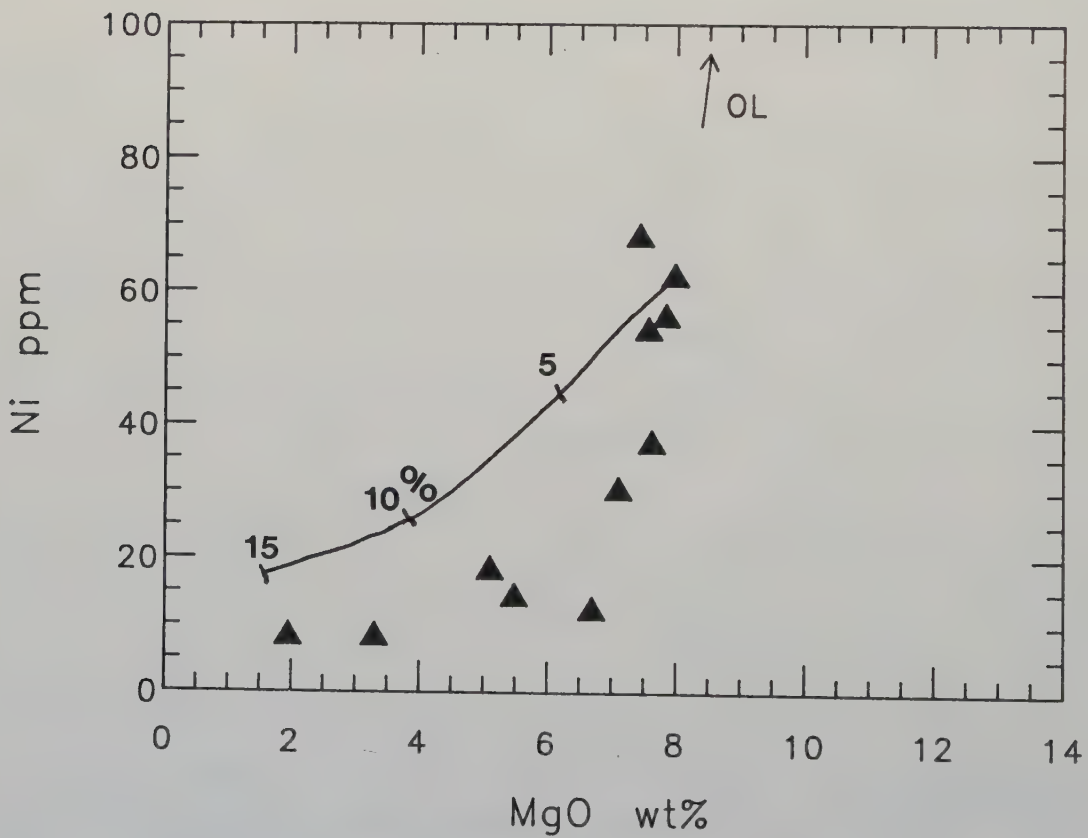


Fig. 8.5. MgO versus Ni for Troodos glasses (triangles). Fractionation trend for olivine crystallization (5%, 10%, and 15%) is shown. Arrow points towards olivine composition.

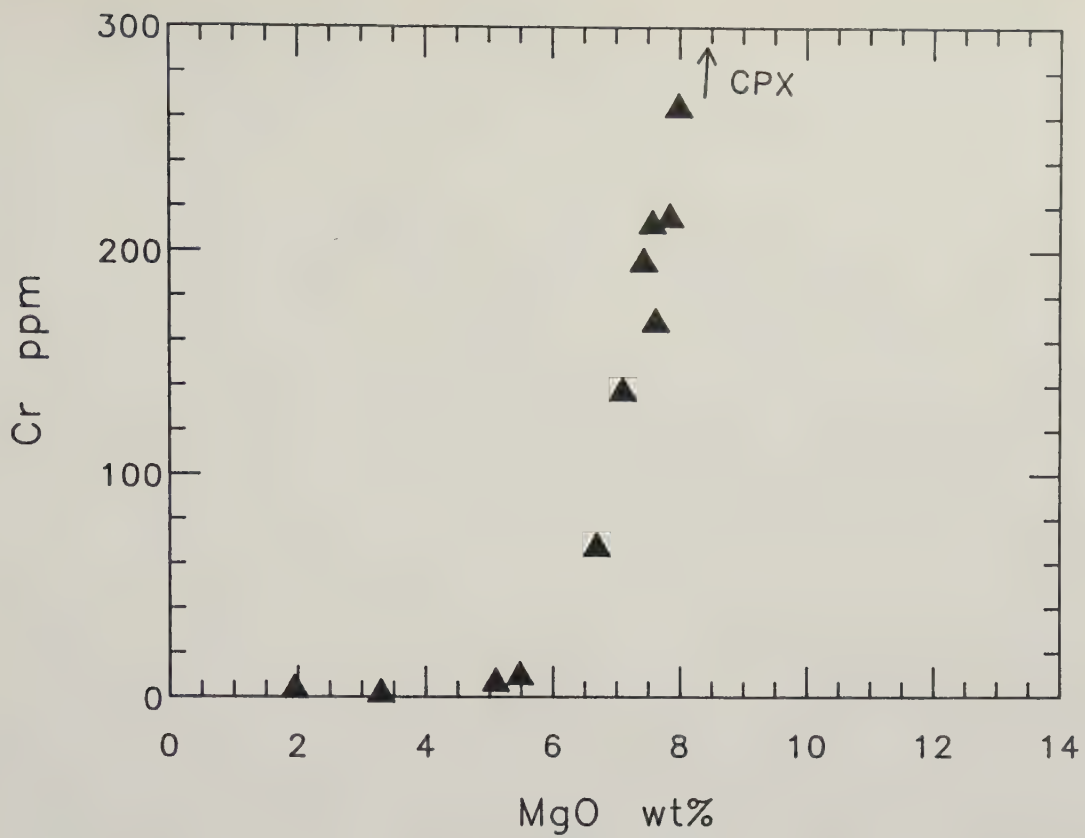


Fig. 8.6. MgO versus Cr for Troodos glasses (triangles). Arrow points towards clinopyroxene composition.

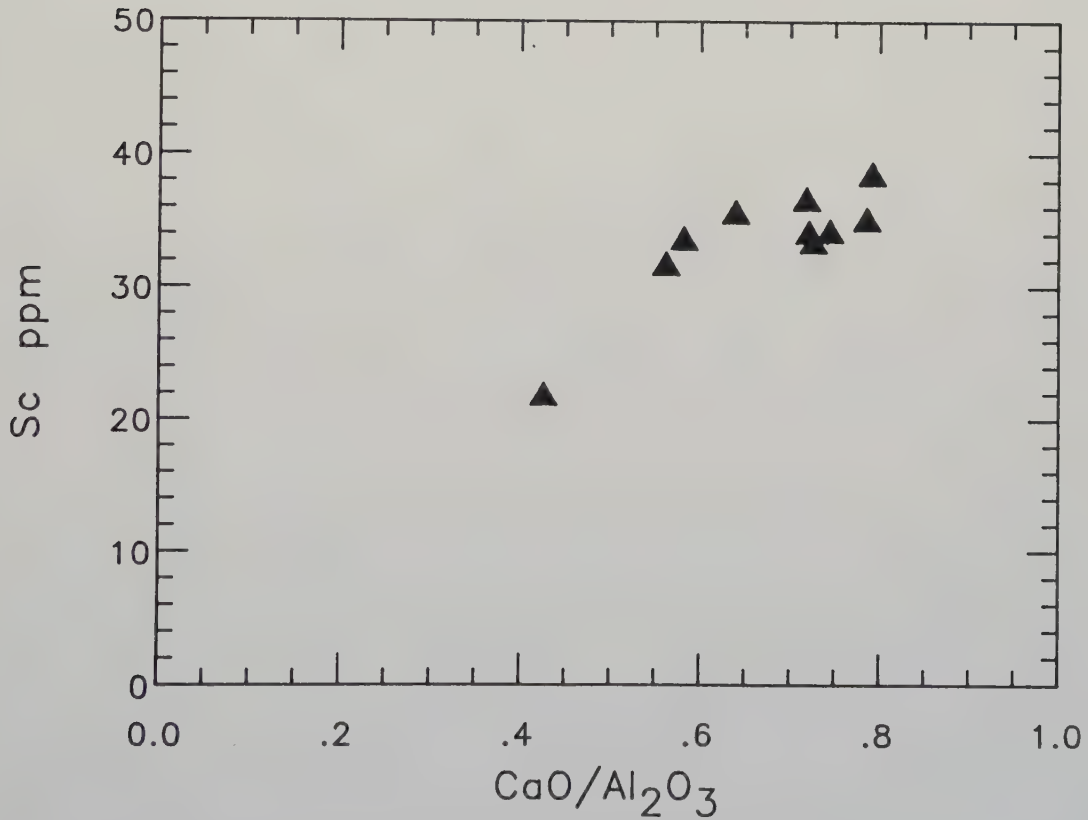


Fig. 8.7. CaO/Al₂O₃ versus Sc for Troodos glasses (triangles).

olivine as a fractionating phase.

Cr and Sc are compatible elements with respect to clinopyroxene (Table 8.2). Clinopyroxene fractionation causes a decrease in MgO and a decrease in CaO/Al₂O₃ ratio, because it incorporates CaO preferentially over Al₂O₃. This effect is seen in Fig. 8.6, 8.7, where the glasses form a trend of decreasing MgO with decreasing Cr, and decreasing Sc with decreasing Al₂O₃. Thus, the trace element data also confirm clinopyroxene as a fractionating phase.

Sr is a compatible element with respect to plagioclase. Eu occurs in two oxidation states as Eu²⁺ and Eu⁴⁺, of which Eu²⁺ can substitute for Sr in plagioclase. In contrast, the other REE are incompatible. Plagioclase fractionation should therefore show up in negative Sr- and Eu-anomalies in the REE patterns of the differentiated lavas. One of the Troodos lavas, a dacite shows such a negative Eu anomaly, confirming that plagioclase was a fractionating phase (Fig. 4.20).

Ti and V are compatible with respect to oxide phases such as ilmenite. Troodos lavas show a decrease of V in one sample, but no decrease of Ti with decreasing MgO. This suggests that oxide phases had only a small influence late in the fractional crystallization history of the Troodos lavas (Fig. 8.8).

Thus, major and trace elements indicate that olivine, clinopyroxene, and plagioclase fractionated during the evolution of the Troodos lavas, and titanomagnetite appeared and only in the late stages of differentiation. These observations are consistent with low pressure fractionation.

However, as noted earlier, the variation in isotopic compositions of the glasses is not consistent with simple, closed system fractional crystallization relationships between mafic and differentiated lavas. In order to assess the relative importance of this process for the generation of the Troodos magmas, an attempt is made to model the effects of fractional crystallization in a quantitative way. For this, the heterogeneous nature of their isotopic compositions is ignored for the moment.

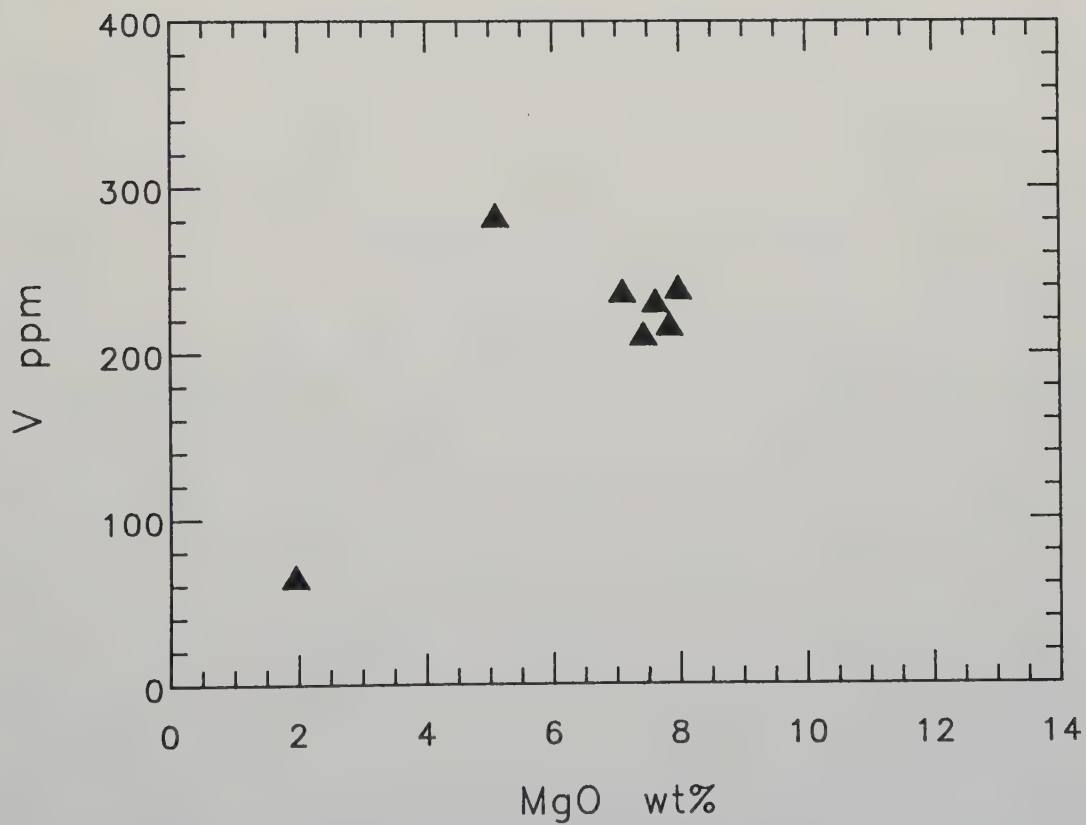
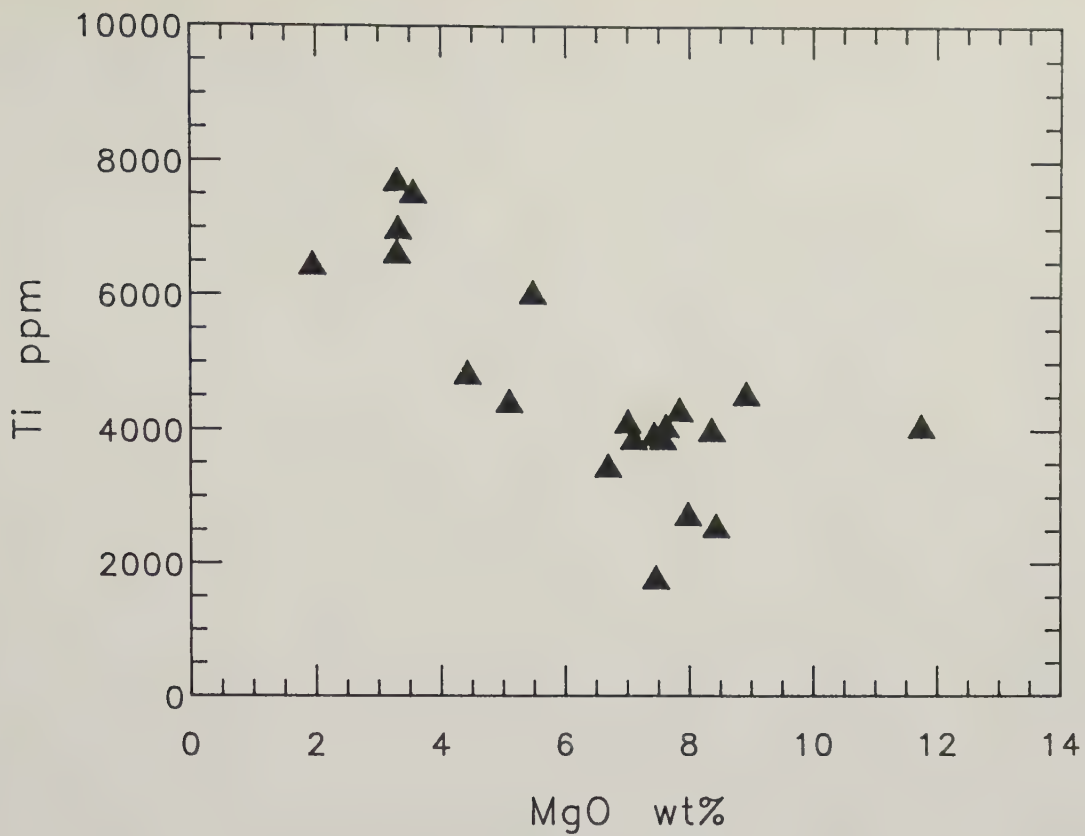


Fig. 8.8. MgO versus Ti and V for Troodos glasses (triangles).

Table 8.2. Partition coefficients (KD values) for fractionating phases.

	1 ol	2 cpx2	3 opx	4 plag
Rb	0.00 a	0.03 g	0.02 c	0.08 g
Ba	0.00 a	0.02 b	0.03 b	0.56 h
Th	0.00 a	0.04 b	0.04 b	0.00 b
K	0.00 a	0.01 k	0.02 e	0.11 e
Ta	0.00 a	0.07 g	0.00 a	0.00 a
Nb	0.00 a	0.10 f	0.15 f	0.01 f
La	0.00 a	0.14 b	0.03 b	0.13 b
Ce	0.00 a	0.20 b	0.02 b	0.12 b
Nd	0.00 a	0.44 b	0.05 b	0.08 b
Sr	0.00 a	0.10 g	0.03 e	2.70 h
Zr	0.00 a	0.10 f	0.03 f	0.01 f
Hf	0.00 a	0.21 b	0.02 b	0.01 e
Sm	0.00 a	0.78 b	0.06 b	0.07 b
Ti	0.00 a	0.60 k	0.10 f	0.04 f
Eu	0.00 a	0.72 b	0.07 b	0.36 b
Gd	0.00 a	0.80 a	0.10 a	0.06 a
Dy	0.00 a	1.20 b	0.21 b	0.03 b
Y	0.00 a	0.50 f	0.20 f	0.03 f
Yb	0.00 a	0.93 b	0.29 b	0.01 b
Lu	0.00 a	0.86 b	0.31 b	0.01 b
Sc	0.30 b	2.00 g	1.10 g	0.01 b
Zn	0.70 i	0.41 i	0.90 i	0.38 i
Mn	1.20 g	0.90 i	1.40 i	0.00 k
Co	1.30 c	1.20 c	2.00 c	0.01 e
Cr	1.10 d	3.00 k	5.90 g	0.02 b
Ni	8.10 d	1.40 g	3.00 g	0.02 b

a assumed value
 b Luhr & Carmichael (1980)
 c Frey et al. (1978)
 d Arndt (1985)
 e Gill (1981)
 f Pearce & Norry (1979)
 g Irving & Frey (1984)
 h Drake & Weil (1975)
 i Henderson (1982)
 j Goodman (1972)
 k Reischmann (1986)

These model calculations can only be approximations, because many factors governing the fractional crystallization process are simplified in the calculations. For example, it is assumed that fractionation occurs in a closed system, and that the major element composition of the fractionating mineral phases is constant and does not change during fractional crystallization. Further, the distribution coefficients for trace elements for each mineral phase are not precisely known.

Quantitative modelling will be carried out for three examples. Three mafic glass compositions were selected, the most mafic one, sample 343 (11.75% MgO), and two mafic ones, samples 316 and 345 (7.84 and 7.98% MgO). At very similar MgO contents, these two samples have different trace element contents (Table 8.3). The fractionation of each of these mafic compositions was calculated towards a differentiated glass composition, sample 370 (3.3% MgO).

Table 8.3. MgO, TiO₂ and Yb of selected glass samples

sample	343	316	345	370
MgO (%)	11.75	7.84	7.98	3.30
TiO ₂ (%)	0.67	0.71	0.45	1.10
Yb (ppm)	2.24	1.78	1.43	2.84

The method of Wright and Doherty (1970), and the major element compositions of glasses and measured mineral phases (Table 8.1) were used to calculate mineral proportions and degree of fractionation for each example. Mn, K, and Ti were considered as trace elements and modelled in the trace element calculations, whereas P₂O₅ was not modelled. The results of the calculations are given in Table 8.4.

In all three cases acceptable solutions were obtained for the major element modelling. For sample 343 to sample 370 only the combination of ol-cpx-plag at a degree of fractionation (F) of 77% with a sum of the squares of the residuals (SSR) of 1.13 was satisfactory. Fractional crystallization from sample 316 to 370 could be modelled with 57% fractionation of ol-cpx-plag (SSR=3.03), or with 71% fractionation of opx-cpx-plag (SSR=0.25). For the fractionation of sample 345 to sample 370 the combination of ol-cpx-plag (F=41%), or opx-cpx-plag (F=52%) gave low SSR, 0.11 and 0.02, respectively. In all calculations plagioclase is the main fractionating phase, followed by clinopyroxene and then olivine or orthopyroxene. Thus, one or two acceptable solutions for fractionation of three different mafic magmas to the same differentiated magma were obtained. This is not

Table 8.4. Results of fractional crystallization modelling for major elements.

	starting magma	target magma	SSR	F %	proportions of fractionating minerals in %			
					ol	opx	cpx	plag
	343	370						
SiO ₂	50.66	59.89	1.13	77	20.7	-	35.7	43.7
TiO ₂	.67	1.10						
Al ₂ O ₃	14.62	13.76						
FeO*	7.54	10.78						
MgO	11.75	3.30						
CaO	13.21	7.73						
Na ₂ O	1.15	2.79						
K ₂ O	.19	.24						
total	99.79	99.59						
	316	370						
SiO ₂	53.36	59.89	a) 3.03	57	14.4	-	33.7	51.9
TiO ₂	.71	1.10	b) .25	71	-	23.2	27.2	49.6
Al ₂ O ₃	15.81	13.76						
FeO*	7.49	10.78						
MgO	7.84	3.30						
CaO	12.42	7.73						
Na ₂ O	2.05	2.79						
K ₂ O	.11	.24						
total	99.79	99.59						
	345	370						
SiO ₂	56.01	59.89	a) .11	41	15.9	-	43.7	40.4
TiO ₂	.45	1.10	b) .02	52	-	23.8	36.2	40.0
Al ₂ O ₃	14.20	13.76						
FeO*	7.79	10.78						
MgO	7.98	3.30						
CaO	11.24	7.73						
Na ₂ O	1.86	2.79						
K ₂ O	.20	.24						
total	99.73	99.59						

SSR = sum of the squares of the residuals between calculated and observed magma

F = degree of fractional crystallization in % of the starting magma

surprising, because the combination of three mineral phases in modelling calculations such as these yields an acceptable solution for the major elements in most cases.

In two cases, the sum of the squares of the residuals is lower in the solution using orthopyroxene. However, orthopyroxene occurs only rarely, whereas olivine is more abundant in the Troodos lavas. Therefore, the solutions with ol-cpx-plag are thought to be more realistic.

The trace element concentrations of the residual lavas were calculated assuming Rayleigh fractionation after the method of Arth (1976). The degree of fractionation and the proportions of phases derived from the major element modelling were used for the trace element modelling. The distribution coefficients (KD values) for trace elements were taken from the literature (Table 8.2). It was assumed that the liquid was in equilibrium with the chemical composition on the surface of the crystals and that the crystals were removed from the liquid after formation.

In Tables 8.5 - 8.6, the calculated results are compared with the measured values of sample 370. Due to the uncertainties in the modelling, the calculated results with deviations of less than 20% were considered to be in agreement with the measured values. The calculated compositions were normalized to the measured abundances of sample 370 and are shown in Fig. 8.9 - 8.11.

Table 8.5. Results of fractional crystallization modelling for trace elements.

	343 meas.	370 meas.	370 calc.
Rb	3.64	5.20	13.67
Ba	27.50	31.40	77.58
K	1550	1860	5771
Nb	0.7	0.9	2.7
La	2.16	2.07	7.45
Ce	6.00	6.14	20.22
Nd	5.31	6.09	16.28
Sr	117.0	80.60	86.76
Zr	40	48	151
Sm	1.93	2.37	5.03
Ti	4017	6590	11658
Eu	.776	.893	1.75
Gd	2.82	3.33	7.33
Dy	3.47	4.34	7.53
Y	28	37	86
Yb	2.24	2.84	5.62
Lu	.341	.424	.89
Mn	1934	1390	3516

370 calc was calculated using ol-cpx-plag.

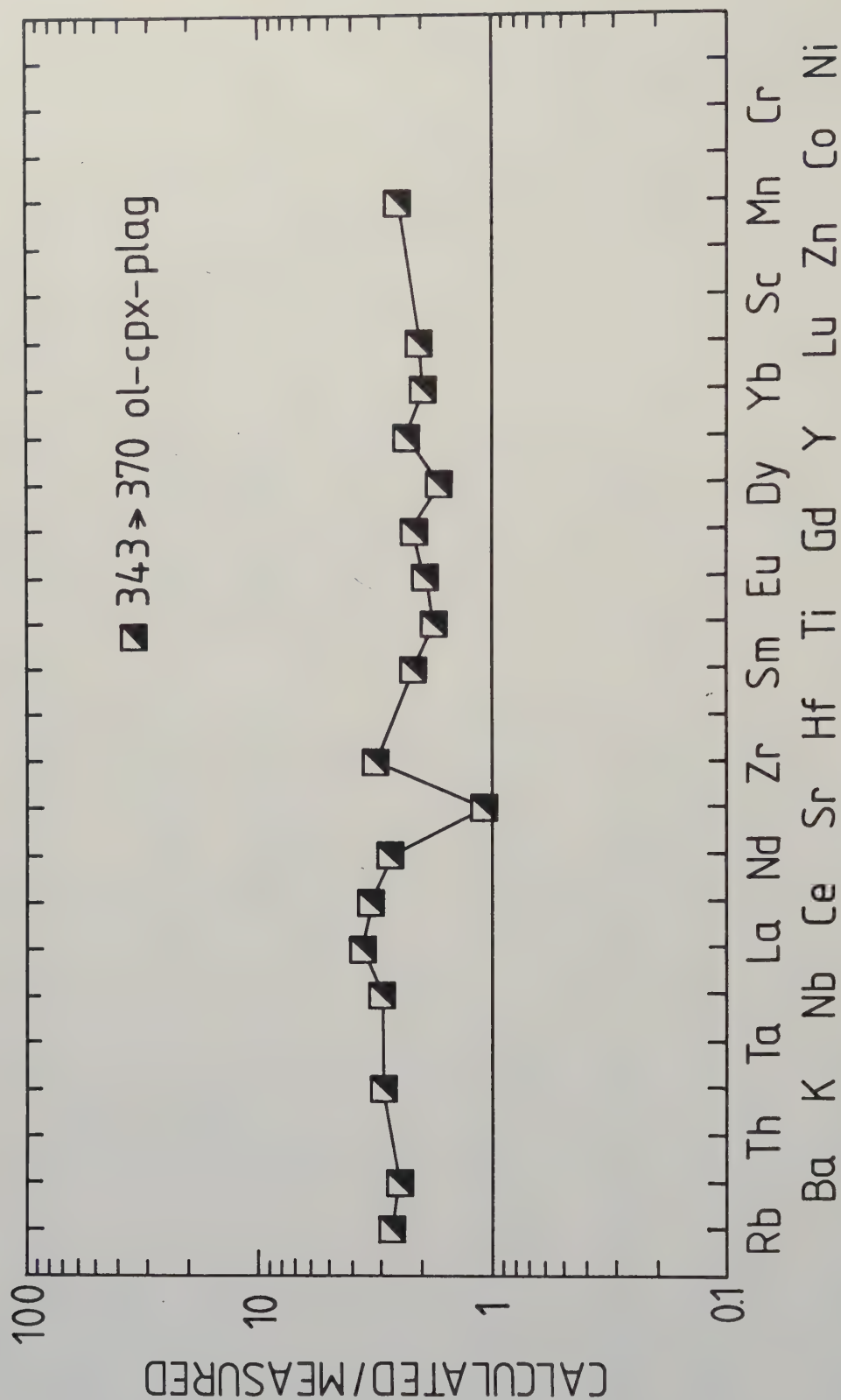


Fig. 8.9. Results of fractional crystallization modelling (ol-cpx-plag) from sample 343 to sample 370 for trace elements. Calculated concentrations are normalized to measured concentrations of sample 370.

1. Fractionation from 343 to 370:

There is an obvious discrepancy between the measured and the calculated composition for all trace elements (Table 8.5, Fig. 8.9). The calculated concentrations are up to three times higher than the measured ones. This suggests that the most mafic sample 343 cannot be related by fractional crystallization to the differentiated sample 370 with respect to trace elements, although such a relationship is consistent with their major element compositions. The observed concentrations can also not be explained with a periodically refilled magma chamber undergoing fractional crystallization as proposed by O'Hara (1977). In that case, the trace element concentrations in the fractionated lava are even higher than for closed system fractionation. The modelled example, however, has lower concentrations than expected from the modelling assuming closed system fractional crystallization.

Table 8.6 Results of fractional crystallization modelling for trace elements.

	316 meas.	370 meas.	316 to 370 calc.a	316 to 370 calc.b	345 meas.	345 to 370 calc.a	345 to 370 calc.b
Rb	2.17	5.20	4.73	6.65	5.36	8.82	10.64
Ba	16.90	31.40	28.21	34.11	22.10	32.22	36.63
Th	.210	.270	.48	.69	.200	.33	.40
K	939	1860	2027	2821	1660	2724	3279
Ta	.039	.058	.09	.13	.071	.12	.14
Nb	0.8	0.9	1.78	2.38	1.2	1.97	2.31
La	1.41	2.07	2.85	3.84	.878	1.38	1.64
Ce	4.22	6.14	8.39	11.31	2.39	3.70	4.39
Nd	4.03	6.09	7.49	9.81	2.43	3.56	4.16
Sr	97.50	80.60	78.97	77.12	68.40	64.85	64.28
Zr	29	48	64	92	22	36.13	43.69
Hf	.950	1.65	2.01	2.83	.770	1.23	1.47
Sm	1.52	2.37	2.53	3.20	1.03	1.39	1.59
Ti	4260	6590	7656	9772	2700	3836	4403
Eu	.619	.893	.92	1.09	.419	.53	.60
Gd	2.25	3.33	3.75	4.67	1.63	2.19	2.49
Dy	2.76	4.34	4.12	4.86	2.16	2.67	2.91
Y	22	37	41	51	14	20	23
Yb	1.79	2.84	2.92	3.44	1.44	1.90	2.08
Lu	.266	.424	.44	.52	.217	.29	.32
Sc	34.9	31.5	41.4	40.5	38.3	39.5	38.5
Zn	58	94	85	89	60	78	80
Mn	1080	1390	1540	1555	1240	1495	1507
Co	35.4	29.6	46.0	41.4	33.7	37.8	35.3
Cr	215	3	195	116	264	219	148
Ni	56	8	41	53	56	45	55
316 to 370 calc.a: ol-cpx-plag					345 to 370 calc.a: ol-cpx-plag		
316 to 370 calc.b: opx-cpx-plag					345 to 370 calc.b: opx-cpx-plag		

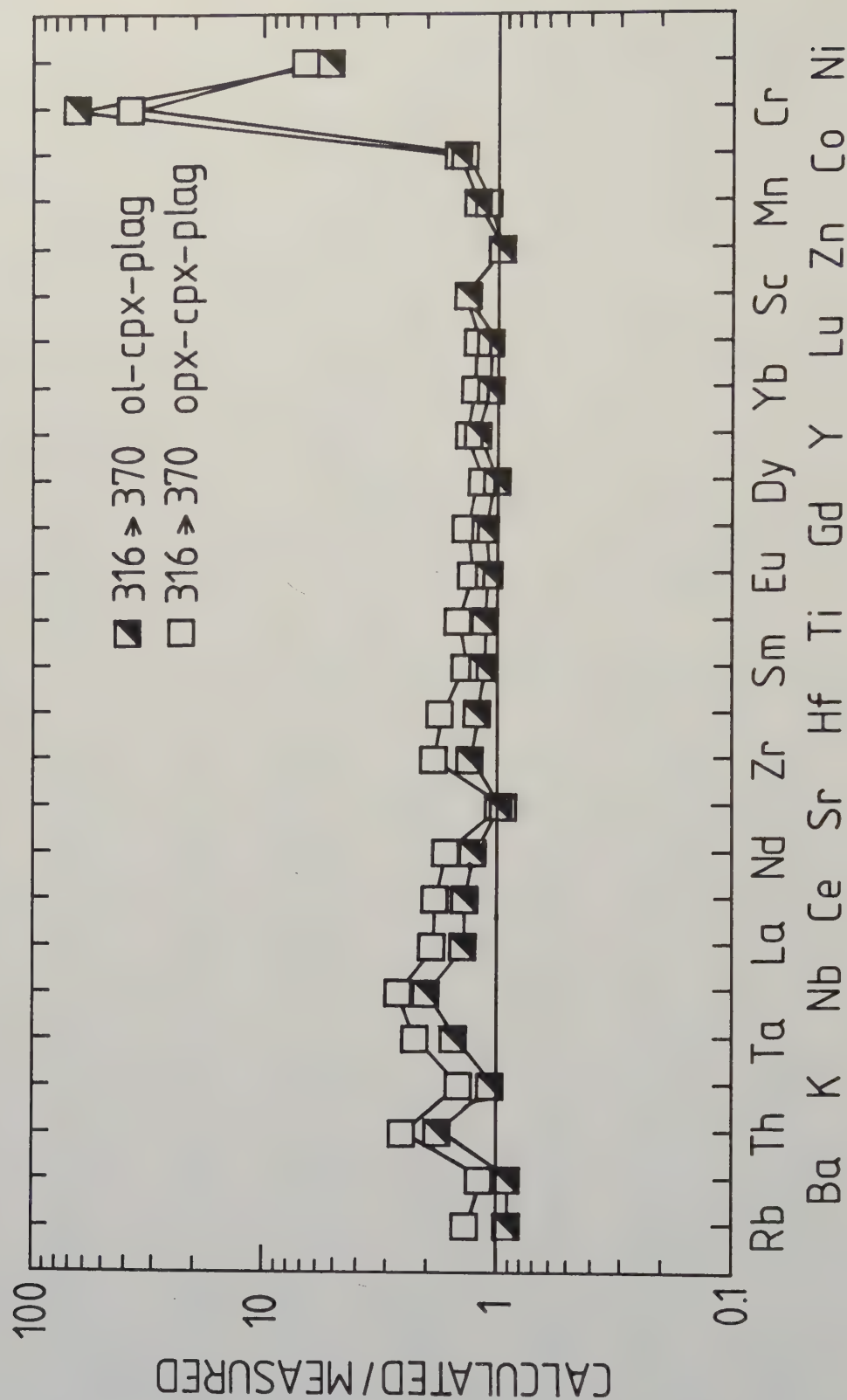


Fig. 8.10. Results of fractional crystallization modelling from sample 316 to sample 370 for trace elements. Calculated concentrations are normalized to measured concentrations of sample 370. ol-cpx-plag: half-filled squares, opx-cpx-plag: open squares.

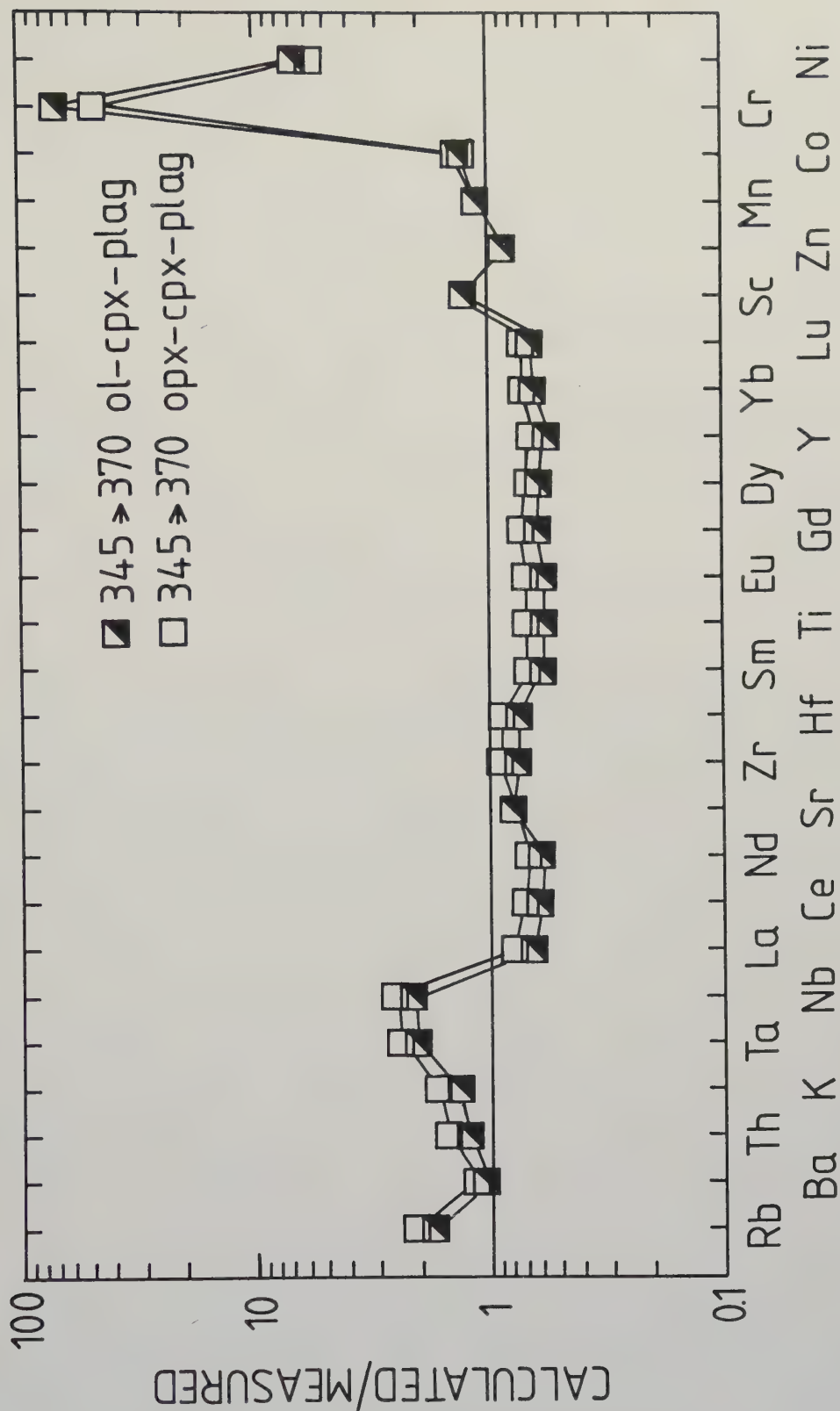


Fig. 8.11. Results of fractional crystallization modelling from sample 345 to sample 370 for trace elements. Calculated concentrations are normalized to measured concentrations of sample 370. ol-cpx-plag: half-filled squares, opx-cpx-plag: open squares.

2. Fractionation from 316 to 370:

The differences between the calculated and the measured trace element concentrations is much lower than in the first case (Table 8.6). Fig. 8.10 shows the relative deviation of the calculated from the measured concentration. The calculation based on ol-cpx-plag is closer to the measured values than the one based on opx-cpx-plag, and both show the same pattern of deviation. In the solution with ol-cpx-plag, the most incompatible elements Rb, Ba and K show a reasonable fit, whereas the calculated Th, Nb and Ta are too high. All of the calculated REE and similarly incompatible elements are also too high but show better agreement with the measured pattern. Of the group of compatible trace elements Sc, Mn and Co are also too high, whereas Zn shows a good agreement. In contrast, Cr and Ni deviate drastically from the measured values, being 65 and 5 times higher, respectively.

3. Fractionation from 345 to 370:

The results of the modelling are given in Table 8.6. The deviations of the calculated concentrations are shown in Fig. 8.11. This case is similar to the previous one in that both combinations of mineral phases, ol-cpx-plag and opx-cpx-plag, show the same pattern of deviation from the measured values. Also, the opx-cpx-plag solution has higher concentrations than the one with ol-cpx-plag. Of the very incompatible elements, Ba and Rb show reasonable agreement, whereas the calculated values K, Th, Ta, and Nb are far too high. The REE and similarly incompatible elements are all lower than the measured values, by about 20 to 30%. The compatible elements Sc, Zn, Mn and Co show only deviations between -14 and 26%, but the calculated concentrations of Cr and Ni are drastically higher than measured, 75 and 6 times higher, respectively.

For all model calculations the agreement between calculated and measured concentrations for the very incompatible trace elements is not very good. This is not surprising as fractional crystallization does not change the ratios between very incompatible elements such as K, Rb, Cs, Ba, and Th, and the starting compositions have quite different ratios of these elements. For example, Ba/Rb of samples 316 and 345 are 7.78 and 4.12, and their Th/Rb ratio is 0.97 and 0.37, respectively. The calculated Nb and Ta concentrations are always too high. One reason for this may be that the KD values are too low, another one may be that

the precision of Nb analyses relatively poor at the low concentrations analyzed. Calculated REE and similarly incompatible element concentrations would fit reasonably well if the starting composition were intermediate between 316 and 345. This indicates that several primary magmas with different trace element contents must have been present and fractionating.

For two of the examples, the calculated compositions (343 to 370) and (316 to 370) shows an underabundance of Sr (Fig. 8.9, 8.10) relative to the other incompatible trace elements, whereas this is not observed in the glass compositions. This may have several reasons. It is possible that the KD used for Sr is too high. However, this is unlikely, because the calculated Sr concentrations fit much better for the other example (345 to 370) (Fig. 8.11). The other possibility is that less plagioclase crystallized than indicated by the model calculations. This is consistent with the lack of Eu anomalies in all but one glass sample (Fig. 4.20). If fractional crystallization took place only to a small degree, this would indicate that several parental magmas with similar major element compositions and different trace element concentrations were present, and each of these fractionated only to a small degree, so that no significant Sr and Eu anomalies formed.

The drastic difference in calculated and measured Cr and Ni contents could be explained by the fractionation of olivine with Cr-spinel inclusions. Another possibility is that the KD's for opx, ol and cpx for these elements could be higher than assumed in the model calculation.

In summary, the results of the quantitative modelling for the major elements are consistent with fractional crystallization of an ol-cpx-plag or an opx-cpx-plag assemblage. In contrast, the results of the trace element modelling do not agree with fractional crystallization from the most mafic glass composition to a differentiated one (343 to 370). For the other examples they are consistent only for some trace elements. This process can account for the variation of trace elements in a qualitative way, but numeric modelling and isotopic ratios do not confirm simple fractional crystallization relationships between the analyzed samples. It is an

important process governing the major element and influencing the incompatible and compatible trace element composition.

8.3 PARTIAL MELTING

Several constraints can be inferred for the mineral composition of the mantle source of the Troodos lavas. Partial melting of a mantle source containing garnet would yield melts that are enriched in the HREE. Troodos lavas, however, have parallel REE-patterns with horizontal distribution of the HREE (Fig. 4.20). This indicates that no garnet was present in the mantle source. Thus, the partial melting probably took place in the spinel stability field under pressures of less than 20 kb. There was probably not much plagioclase present in the mantle source, because there are no pronounced Eu anomalies in the lavas (Fig. 4.20).

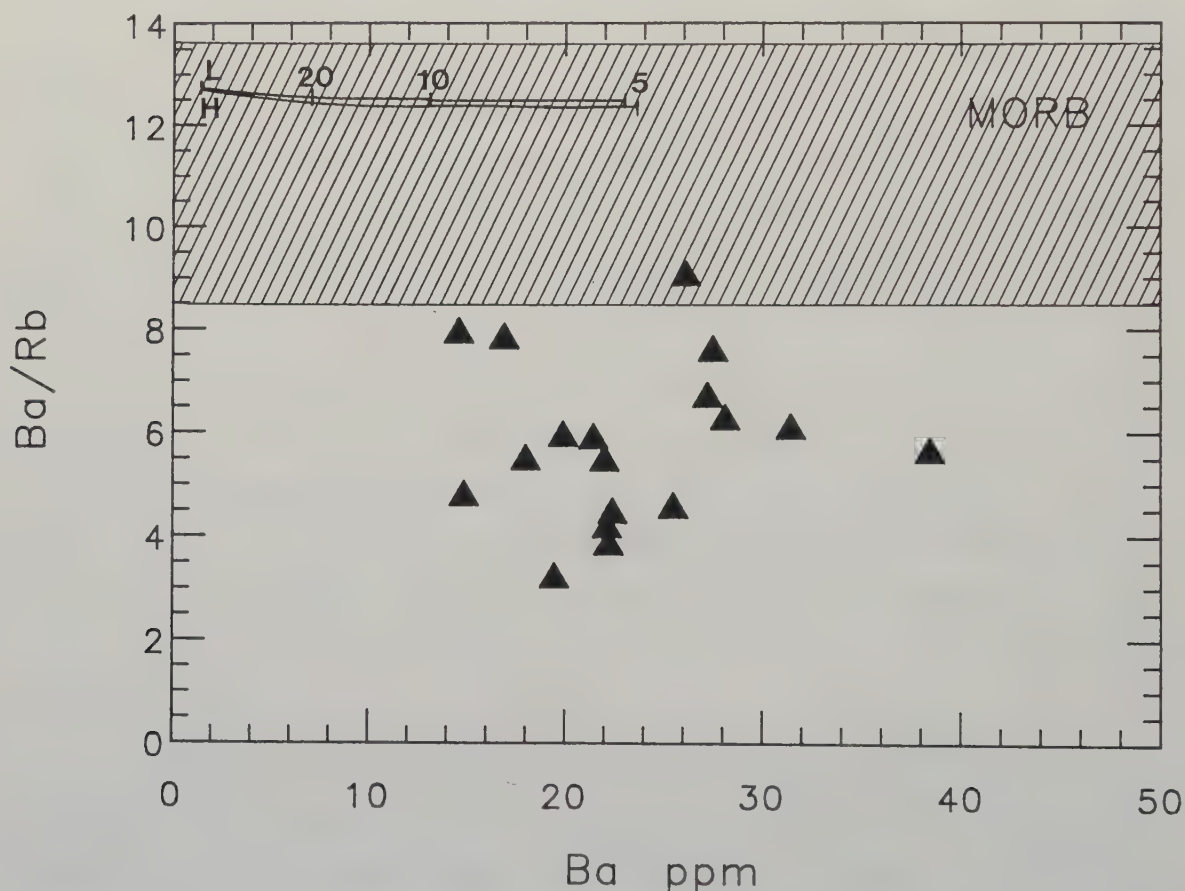


Fig. 8.12. Ba versus Ba/Rb for Troodos glasses (triangles). The MORB field is given for comparison. Partial melting trends for a harzburgite (H) and spinel lherzolite (L) source are shown. Different degrees of partial melting yield melts with different Ba concentrations but nearly constant Ba/Rb ratios.

The observed variation in incompatible element abundances of mafic Troodos glasses is characterized by in part similar incompatible trace

element ratios, e.g. between the REE, or in part variable trace element ratios, e.g. Ba/Rb or K/Rb (Fig. 8.12). In addition, the incompatible elements occur at different concentrations, even in the mafic lavas.

The quantitative modelling of fractional crystallization was able to reproduce some of the incompatible trace element ratios, e.g. between the REE, but failed to account for the absolute concentrations of these elements or other trace element ratios, e.g. Ba/Rb. Different degrees of partial melting yield different concentrations in the melt, but do not change the ratios of incompatible elements.

In order to illustrate this effect on very incompatible trace element concentrations and ratios, partial melting was modelled for two extreme examples. For these calculations batch melting was assumed. Two compositions for a depleted mantle peridotite were used, a modal composition of 70% olivine and 30% orthopyroxene, and a composition of 66% olivine, 20% orthopyroxene, 12% clinopyroxene, and 2% spinel. The trace element concentration of the mantle source were taken as 1/10 of those observed in N-MORB (Table 7.4). This assumes that N-MORB was generated by 10% of partial melting, or 20% of partial melting and 50% fractional crystallization of olivine. KD values for Rb and Ba are given in Table 8.2. The concentrations of Rb and Ba in the final liquid were calculated for degrees of 5, 10 and 20% partial melting. The results of the model calculations are shown in Fig. 8.12.

The modelling shows that both compositions of mantle peridotite yield similar concentrations of Rb and Ba for a given degree of partial melting. The concentrations of trace elements in the melt vary with the degree of melting, whereas the ratios between the very incompatible elements remain nearly constant during the different degrees of partial melting.

If, in the case of the Troodos magmas, only a single mantle source were partially molten to different degrees, the absolute abundances of the incompatible trace elements would be variable, but the ratios between the very incompatible elements should remain nearly constant. This is consistent with some of the trace element characteristics of the mafic Troodos lavas, e.g. for the concentrations of and ratios between the REE. Different degrees of partial melting, however, do not

change the ratios between incompatible trace elements, e.g. Ba/Rb (Fig. 8.12), or of Sr, Nd, and Pb isotopic ratios and can therefore not account for the variation in these ratios. Thus the observed chemical variation must be caused by further processes, e.g. mixing of magmas or mantle sources of different chemical composition.

8.4 MIXING IN THE MANTLE SOURCE

8.4.1 INTRODUCTION

The low Nd, high Sr and Pb isotopic ratios of the Troodos lavas relative to N-MORB, and the geochemical similarity to island arc tholeiites in trace elements, e.g. the negative Nb-Ta anomaly and the enrichment of alkalis and alkaline earths over REE suggests that magmas of the Troodos ophiolite were generated in an island arc environment (see Chapter 7).

Several mechanisms have been proposed to generate island arc magmas by interaction of mantle components present in a subduction zone, namely the subducted oceanic sediment and oceanic crust and the mantle wedge overlying the subducted slab. It has been debated which of these components contribute to the genesis of island arc magmas. Several models exist, as summarized by White and Dupré (1986):

- 1) (depleted) mantle peridotite and subducted (altered) oceanic crust (e.g. Meijer, 1976);
- 2) hot spot or "oceanic island" type mantle (e.g. Arculus, 1981, Stern, 1982, Morris & Hart, 1983);
- 3) subducted sediment and (depleted) mantle peridotite $\pm$ subducted oceanic (altered) crust (e.g. Armstrong, 1971, Kay, 1980, Perfit, et al. 1980).

Model (2) does not seem to be consistent with the chemical characteristics of island arc volcanics. Hofmann et al. (1986) have demonstrated that the Nb/U ratio is constant in all MORB and oceanic island basalts, but lower and variable in island arc volcanics. Thus, island arc volcanics cannot be generated by an oceanic island mantle source alone, unless the Nb/U ratios is extremely fractionated by a Nb-retaining residual mineral phase at the time of magma generation. This leaves alternatives (1) and (2).

The enrichment in LFS elements relative to REE and HFS in supra-subduction zone volcanism today is believed to be caused by the modification of the upper mantle wedge by incompatible element-rich fluids and/or subducted sediment (Ringwood, 1974, Kay, 1980, Saunders et al, 1980, Gill, 1981, Arculus & Powell, 1984, White & Patchett, 1984, White & Dupré, 1986). Several authors have argued that subducted pelagic sediment is required to explain the isotopic characteristics of island arc volcanism, particularly the $^{143}\text{Nd}/^{144}\text{Nd}$ ratios lower than the mean value for MORB and the enrichment in $^{207}\text{Pb}/^{204}\text{Pb}$ (Kay, 1980, Saunders & Weaver, 1980, White & Patchett, 1984, White, 1985, White & Dupré, 1986).

Troodos glasses have $\epsilon_{\text{Nd}}(\tau=80\text{Ma})$ of +6.5 to +7.5, which is low compared to a value of +9.4 for a mean of N-MORB age-corrected for 80 Ma (Fig. 7.8). Furthermore, the glasses show enrichment in $^{207}\text{Pb}/^{204}\text{Pb}$ versus $^{206}\text{Pb}/^{204}\text{Pb}$ (Fig. 7.9) relative to the values of N-MORB. These isotopic compositions suggest that a sedimentary component has played a significant role in generating the geochemical characteristics of the Troodos magma source.

In the following section an attempt is made to model the chemical composition of the Troodos glasses with a mixing calculation using mantle components of the subduction zone environment, namely depleted mantle and sediment.

8.4.2 ASSUMPTIONS MADE FOR MIXING CALCULATION

The lack of knowledge of the compositions of the mantle components and the complexity of the processes operating in modern subduction zones makes it difficult to model the relative proportions of these components in the genesis of modern island arc magmas. Several simplifying assumptions have been made for this modelling regarding the compositions of the mantle components and the mixing process:

1. For the modelling, only a two component mixing process is considered: a sediment end member (representing the subducted sediment) will be mixed with a depleted mantle end member (representing the mantle wedge overlying the subducted slab). The potential influence of subducted oceanic crust will not be considered for these calculations, but will be treated later.

2. Mixing of the depleted mantle wedge and sediment is assumed to have taken place in the mantle source, before or at the same time as partial melting gave rise to the magmas.

3. The REE patterns of mafic lavas are interpreted to be derived from partial melting of the mixture of depleted mantle wedge and sediment.

4. It is assumed that incompatible trace elements are not fractionated during partial melting. This is true for higher degrees of partial melting, as demonstrated in section 8.3. The fractionation that may occur during very small degrees of partial melting is assumed to be negligible for this calculation. Further, incompatible trace element ratios are assumed to be unchanged by fractional crystallization. Thus the ratios abundances of incompatible elements observed in the glasses are assumed to represent those of the mantle source.

5. The low Nd isotopic compositions of the Troodos glasses compared to those of age-corrected N-MORB (ϵ_{Nd} of +7 and +9.6, respectively) are assumed to be the result of sediment addition to a depleted mantle end member.

The modelling will be done in several steps:

1. Suitable end-members for the sediment and depleted mantle end member are chosen. These are used to calculate how much sediment is necessary to shift the ϵ_{Nd} value from age-corrected N-MORB (+9.6) to that of Troodos glasses (+7).

2. The REE of the depleted mantle end member used above represent a mixture of sediment and depleted mantle. To obtain the uncontaminated depleted mantle, they are corrected for this amount of sediment, i.e. the proportion of the REE concentrations caused by sediment addition is subtracted. This results in a more REE-depleted mantle end member. The other incompatible trace elements (Cs, Rb, Ba, Th, K, Ta, Nb and Sr) are then interpolated so that the incompatible trace elements of the uncontaminated mantle end member form a smooth pattern on a normalized concentration plot, similar to the pattern of N-MORB.

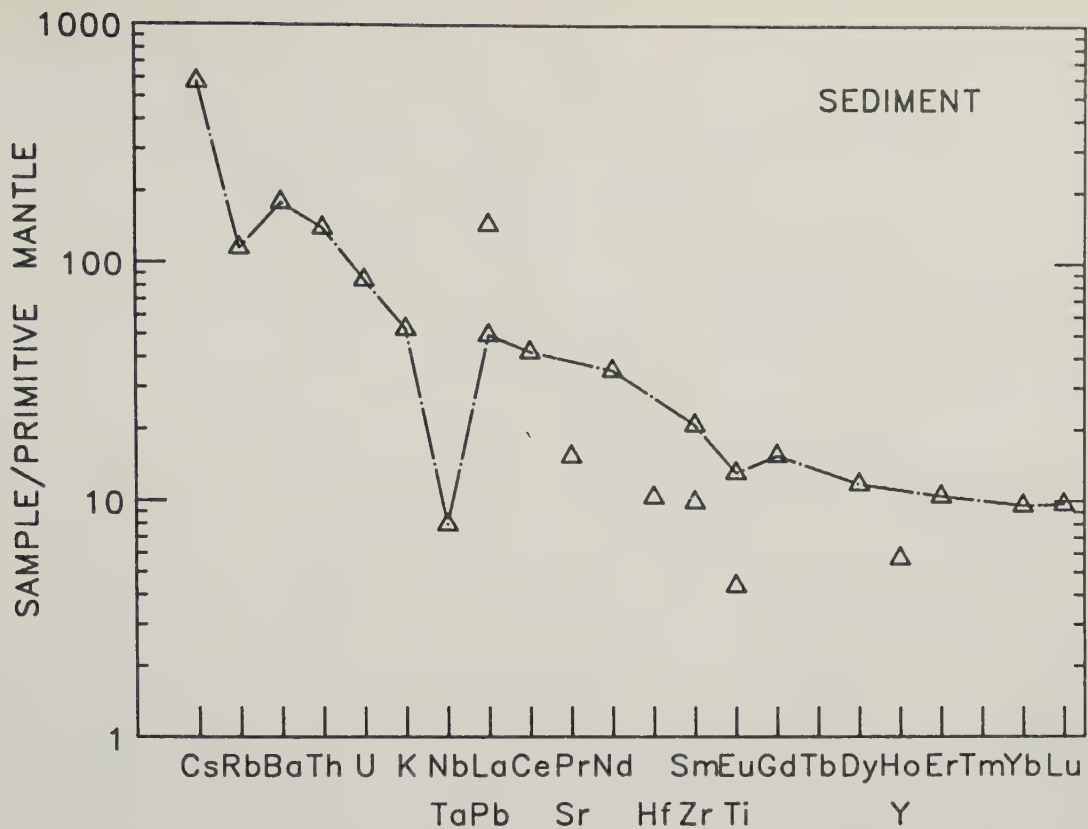


Fig. 8.13. Trace element concentrations of average pelagic sediment (normalized to primitive mantle). Data from Ben Othman, White, Patchett (unpublished) and Jenner et al.(1987). Note the negative Rb anomaly relative to Ba and the negative anomaly of Nb relative to the REE.

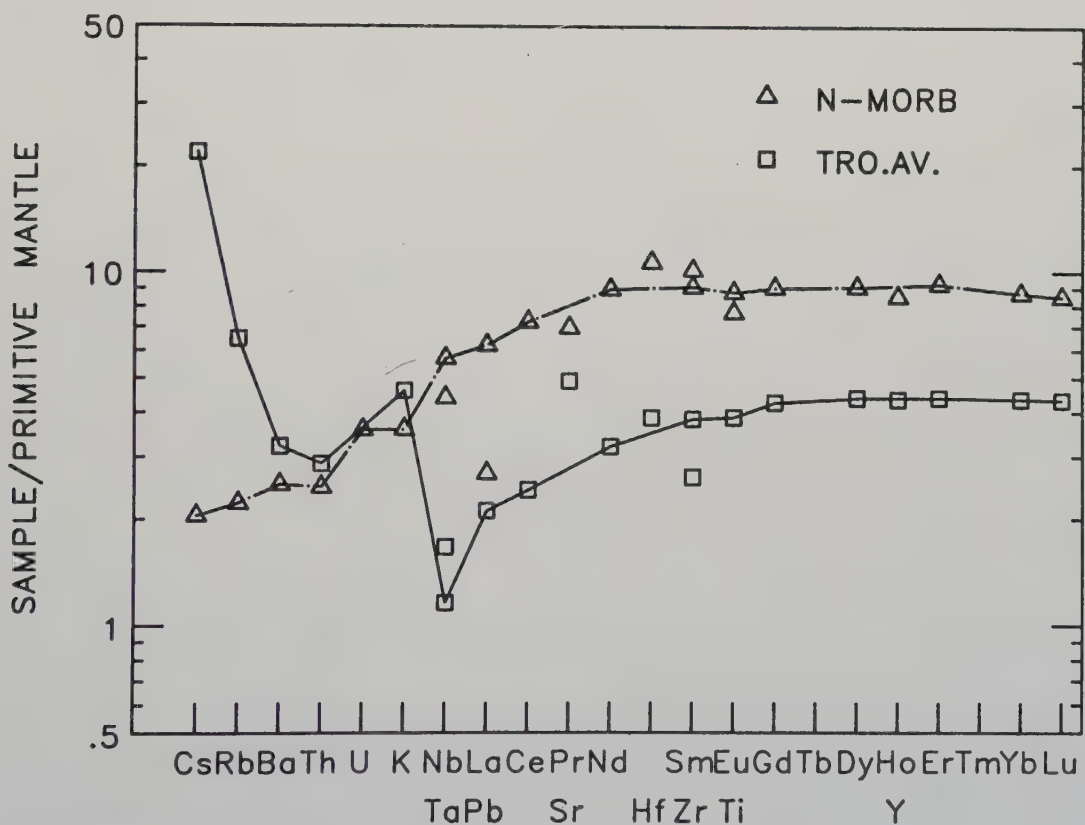


Fig. 8.14. Trace element concentrations of N-MORB (Jochum et al.(1983, 1986), Hofmann et al.(in prep.), and an average of mafic Troodos glasses (Table 7.4, 8.7) (normalized to primitive mantle).

3. This uncontaminated mantle end member is mixed with the amount of sediment necessary to shift the ϵ_{Nd} value (derived from 1.) The concentrations and isotopic compositions of the calculated mixtures are compared with the observed chemical composition. The observed and calculated compositions show good agreement, except for the water-soluble incompatible elements (Cs, Rb, K, Sr).

4. The previous calculations did not account for the variation in REE concentrations and in ϵ_{Nd} values of the Troodos volcanics. Lavas with U-shaped REE patterns and very low ϵ_{Nd} of +1 are found in other areas of the Troodos ophiolite. These compositions can be modelled with a similar mixing calculation, by using an extremely depleted mantle end member. This suggests that the depleted mantle end member was heterogeneous in incompatible trace elements before it was contaminated with sediments.

5. An attempt is made to explain the underabundance of Cs, Rb, K, and Sr in the calculated mixture compared with the observed trace element compositions. It is suggested that a third component, namely an incompatible element rich fluid phase derived from the subducted slab causes the additional enrichment in these elements.

8.4.3 HOW MUCH SEDIMENT WAS NECESSARY?

In this section, a sediment component and a depleted mantle component are determined and it is calculated how much sediment is necessary to shift the ϵ_{Nd} from age-corrected N-MORB (+9.6) to that of Troodos glasses (+7).

The composition of the sediment component used is given in Table 8.7. An average of 22 modern oceanic sediments (terrigenous sediments, clay, and minor carbonates) was taken (Ben Othman, White, Patchett, unpublished data, Jenner et al., 1987). This data set did not contain Nb concentrations. Nb was interpolated, assuming that trace elements have the same relative abundances in this sediment average as in other averages compiled by Taylor & McLennan (1985) and Chester & Aston (1976). Note that the sediment shows a negative Nb anomaly relative to the other incompatible elements on an extended REE plot (Fig. 8.13). The relative abundance of Ce relative to La and Sm varies in oceanic sediments. The REE patterns may show no Ce-

Table 8.7. Composition of sediment end member and Troodos mafic average

	sediment	Troodos average (Tro.av.)
K	14100	1228
Rb	57.80	3.26
Cs	3.68	.140
Sr	270	86.05
Ba	1020	18.31
Hf	2.79	1.04
Zr	98	26
Ta	-	.06
Nb	5.00	.73
U	1.78	-
Th	10.50	.215
Pb	25.40	-
Y	23	17.5
La	31.90	1.35
Ce	70	4.01
Nd	43.4	3.94
Sm	8.35	1.52
Eu	1.97	0.580
Gd	8.25	2.26
Dy	7.78	2.90
Er	4.53	1.90
Yb	4.11	1.87
Lu	0.640	0.286
Ti	4960	3860
$^{87}\text{Sr}/^{86}\text{Sr}_{80}$	.70900	.703600
$^{143}\text{Nd}/^{144}\text{Nd}_{80}$	.512279	.512906
$^{206}\text{Pb}/^{204}\text{Pb}$	18.762	18.625
$^{207}\text{Pb}/^{204}\text{Pb}$	15.658	15.570
$^{208}\text{Pb}/^{204}\text{Pb}$	38.847	38.484

sediment: Ben Othman, White, Patchett (unpublished data), Jenner et al. (1987). Nb was interpolated after Chester & Aston (1976), Taylor & McLennan (1985).

Troodos mafic average: samples 305, 316, 331, 345, 371, 544.

anomalies, or small positive or negative ones (White et al., 1985, White & Dupré, 1986). For this calculation a sediment component with no Ce-anomaly was selected. The isotopic composition of Nd was age-corrected in the same way as for the Troodos lavas. The Sr isotopic ratio was assumed to be 0.709, higher than that of seawater at Cretaceous time (0.7074, Burke et al., 1982), because oceanic sediments usually have higher $^{87}\text{Sr}/^{86}\text{Sr}$ than present seawater (White & Dupré, 1986). Pb isotopic ratios were not age corrected, because Troodos glass Pb isotopic compositions were not age-corrected either, due to lack of data for U and Pb concentrations.

A simple assumption for the depleted mantle end member would be a N-MORB source ($^{143}\text{Nd}/^{144}\text{Nd}$ age-corrected for 80 Ma, and incompatible trace element concentrations of one tenth of those observed in N-MORB today), as assumed for a similar mixing calculation by White & Dupré (1986). However, the REE in the Troodos glasses are more LREE depleted than those of N-MORB, ($(\text{La}/\text{Yb})_{\text{N}}=0.4 - 0.5$ and 0.7 (Jochum et al. unpublished data), respectively). Furthermore, the low absolute concentrations of REE are lower in the Troodos glasses than in N-MORB (Fig. 7.7). This is important, because the pattern of an average of mafic Troodos glasses (Table 8.7, Fig. 8.14) is assumed to represent a mixture of uncontaminated, depleted mantle wedge and sediment. This means that the uncontaminated mantle end member must have been even more depleted in very incompatible trace elements than the Troodos glasses. The mantle region prior to contamination may have been oceanic lithosphere, residual from a melting event which generated the basalt of oceanic crust. If this depletion event occurred only a short period of time before the mixing, the isotopic compositions in the residue did not have time to change until the mixing took place. Given a longer period of time between the depletion event and the mixing, the fractionated Sm/Nd ratio of the residue would cause an increase of the $^{143}\text{Nd}/^{144}\text{Nd}$ ratio relative to N-MORB_{80Ma} values. Therefore it is assumed for this calculation that the depletion event took place shortly before the mixing event, and thus that the isotopic compositions of the mantle end member is represented by that of N-MORB, age-corrected for 80 Ma. This age-correction presents another problem. The Sm/Nd ratio of the depleted mantle must be higher than that of N-MORB, because of the larger depletion in very incompatible trace elements. Further it has to be higher than that of Troodos glasses, because these represent a mixture between a depleted mantle end member and sediment. However, the Sm/Nd ratio of the uncontaminated depleted mantle is not known, and as an approximation, the $^{147}\text{Sm}/^{144}\text{Nd}$ ratio of the mafic average of Troodos glasses is used for the age-correction of the Nd isotopic ratio of the depleted mantle end member.

It is impossible to determine the absolute concentrations of Nd and other incompatible trace elements in the depleted mantle end member, because the degrees of partial melting and fractional crystallization of the lavas are not known. The degree of partial

melting may have been about 10%, as assumed for generation of N-MORB, or possibly higher, because H₂O rich fluids rising from the subducted slab may have induced melting in the overlying mantle wedge as proposed by e.g. Ringwood (1974), Kay (1980), Gill (1981). Two cases will be considered (Table 8.8) for this source component:

- (1) The concentrations of incompatible trace elements are one tenth of those of the mafic average of Troodos glasses. This approach is used in a similar calculation performed by White & Dupré (1986), assuming that 10% of partial melting (or 20% of partial melting and 50% fractional crystallization of olivine) gave rise to the lavas.
- (2) The concentrations of incompatible trace elements are one fifth of those in the mafic average of Troodos glasses, assuming 20% partial melting of the mantle source (Table 8.8).

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Table 8.8. ¹⁴³ Nd/ ¹⁴⁴ Nd ₈₀ of mantle, sediment, mantle-sediment mixtures, and Troodos average.						
	¹⁴³ Nd ¹⁴⁴ Nd ₀	¹⁴⁷ Sm ¹⁴⁴ Nd	¹⁴⁴ Nd ¹⁴⁴ Nd ₈₀	Nd ppm	ε _{Nd80}	sediment %

sediment	.51234	.1163	.512279	43.4	-5.9	100
case 1						
mantle	.51315	.255	.513028	.394	+9.6	0
mix			.512921		+7.5	.15
case 2						
mantle	.51315	.255	.513028	.788	+9.6	0
mix			.512892		+7.0	.4
Tro.av.			.512906		+7.2	

sediment and Troodos average (Tro.av.): see Table 8.7.						
mantle (1),(2): ¹⁴³ Nd/ ¹⁴⁴ Nd is that of N-MORB, age-corrected for 80 Ma.						
Nd concentrations are 1/10 of N-MORB (Table 7.4) for (1), and 1/5						
of N-MORB for (2).						
mix: mixtures between mantle and sediment.						
=====						

For case (1), the amount of sediment necessary to shift the Nd isotopic ratio from the depleted mantle value to the one observed in the average mafic Troodos glasses was 0.15%, for case (2), 0.4% (Table 8.8). The amount of sediment required depends on the absolute

Table 8.9. Subtraction of sediment component of Troodos average REE patterns to obtain the REE of the uncontaminated mantle end member.

	case 1		case 2	
	1/10 of Tro.av.	uncontaminated mantle (1)	1/5 of Tro.av.	uncontaminated mantle (2)
La	.135	.0873	.270	.143
Ce	.401	.296	.802	.524
Nd	.394	.329	.788	.617
Sm	.152	.140	.304	.272
Eu	.058	.0551	.116	.108
Gd	.226	.214	.452	.421
Dy	.290	.279	.580	.551
Er	.190	.183	.380	.363
Yb	.187	.181	.374	.359
Lu	.0286	.0277	.0572	.0548
(La/Yb) _N		.318		.263

uncontaminated mantle (1): 1/10 Tro.av.-0.15% sediment
uncontaminated mantle (2): 1/5 Tro.av.-0.4% sediment
Tro.av. is given in Table 8.7.

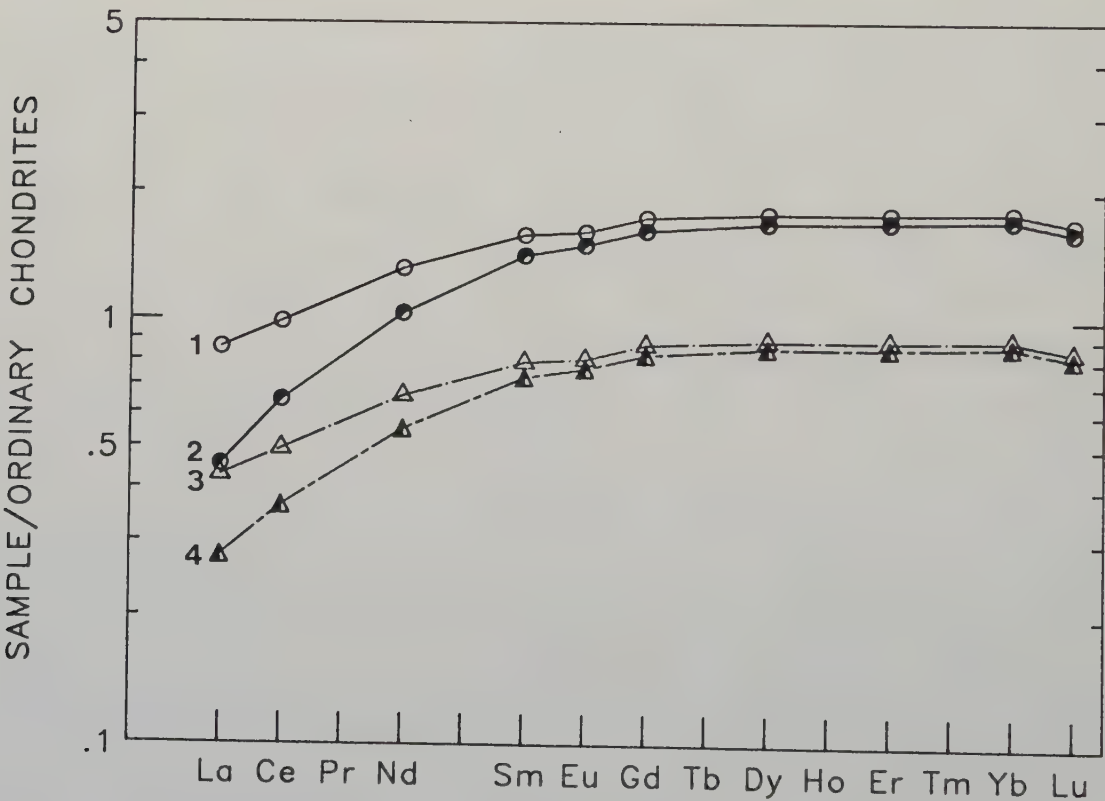


Fig. 8.15. REE concentrations (normalized to chondrites) of Troodos average uncontaminated mantle. Case (2): 1. contaminated mantle, 2. uncontaminated mantle, after subtraction of 0.4% sediment. Case (1): 3. contaminated mantle, 4. uncontaminated mantle, after subtraction of 0.15% sediment.

concentrations of Nd in the mantle end member: the lower these are, the less sediment is necessary cause the observed change in $^{143}\text{Nd}/^{144}\text{Nd}$.

8.4.4 INCOMPATIBLE TRACE ELEMENTS OF THE DEPLETED MANTLE WEDGE PRIOR TO CONTAMINATION

According to the above model, the REE pattern of the average of Troodos glasses represents a mixture of the depleted mantle and sediment component. To obtain the REE pattern and concentrations of the mantle component prior to contamination, the proportion of the REE due to sediment contamination, as derived from Nd isotopes, was subtracted. In case (2), the proportion of sediment added to the mantle end member is higher (0.4%) than in case (1) (0.15%). Thus, a higher percentage of REE is subtracted from the REE pattern of the average of mafic Troodos glasses to obtain the pattern of the uncontaminated mantle end member, resulting in a very LREE-depleted pattern. Table 8.9 and Fig. 8.15 show the calculated REE patterns of the uncontaminated mantle end member for cases (1) and (2). $(\text{La}/\text{Yb})_N$ is 0.318 for case (1) and 0.263 for case (2).

Table 8.10. Extrapolated uncontaminated mantle, mixture of this mantle end member and sediment, and Troodos average for case 1 and 2.

case 1				case 2		
	mantle(1)	calculated mixture	1/10 Tro.av.	mantle(2)	calculated mixture	1/5 Tro.av.
Cs	.000097	.005617	.014	.000124	.01484	.028
Rb	.0106	.0972	.326	.0141	.245	.652
Ba	.163	1.692	1.831	.228	4.31	3.66
Th	.002941	.0187	.0215	.00422	.0462	.043
U	.00113	.00380	-	.00168	.00880	-
K	19.48	40.61	122.8	29.90	86.18	245.6
Ta	.00360	-	.0060	.00568	-	.012
Nb	.0624	.0698	.073	.0982	.118	.146
Pb	.0236	.0617	-	.0394	.141	-
Sr	3.96	4.36	8.61	6.95	8.00	17.21
$(\text{Cs}/\text{La})_N$.111				.087		

mantle (1),(2): very incompatible trace elements were extrapolated from the calculated REE patterns (Table 8.9).
calculated mixture: mixture between extrapolated uncontaminated mantle and sediment.
Troodos average (Tro.av.) is given in Table 8.7.

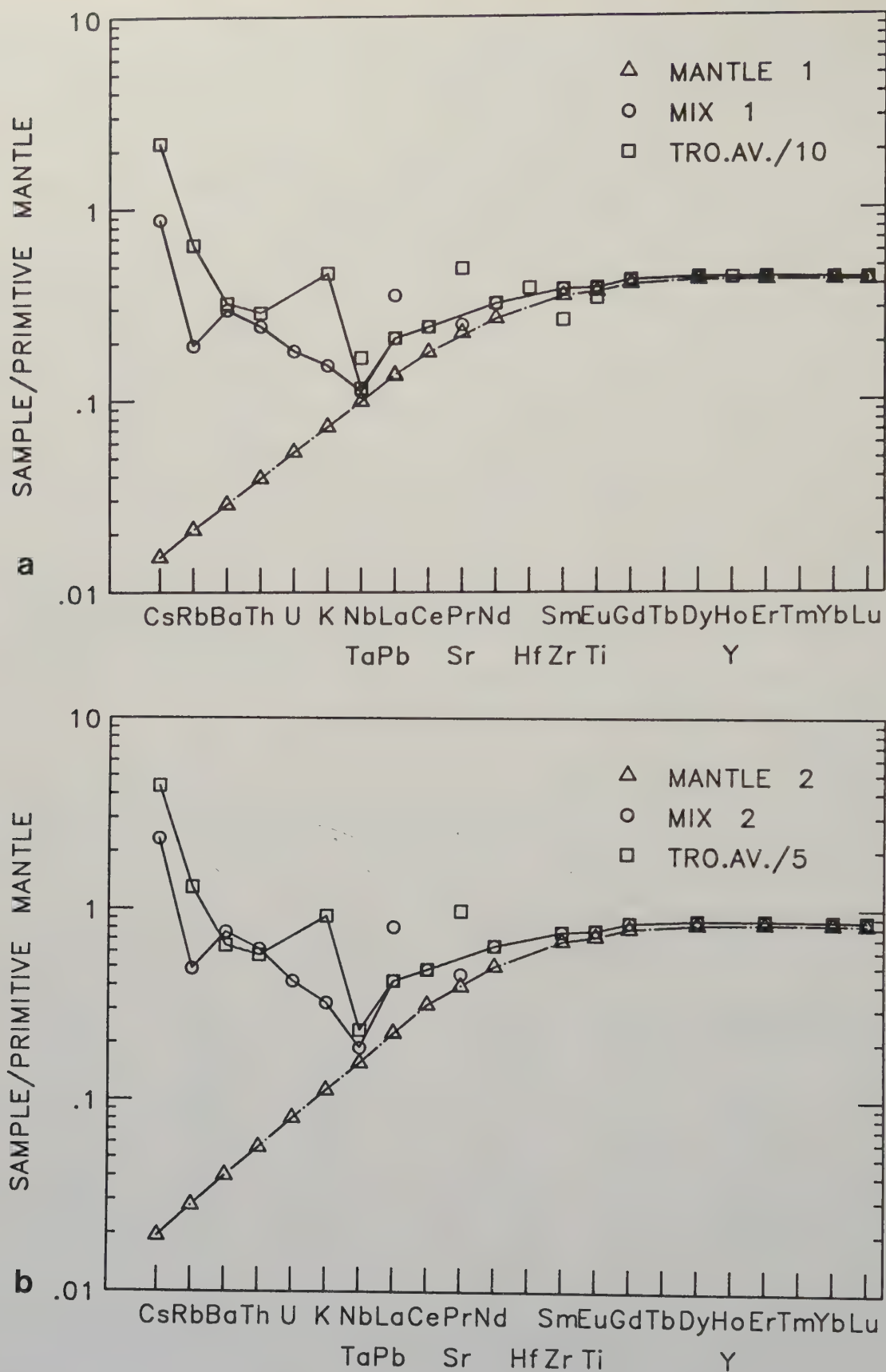


Fig. 8.16. Trace element concentrations of depleted mantle, average of mafic Troodos glasses (Tro.av.) and calculated mixtures between uncontaminated depleted mantle and sediment for case 1 (a) and 2 (b), (normalized to primitive mantle).

Table 8.11. $^{87}\text{Sr}/^{86}\text{Sr}$ of uncontaminated mantle, sediment, calculated mixtures, and Troodos average.

	$\frac{^{87}\text{Sr}}{^{86}\text{Sr}_0}$	$\frac{^{87}\text{Rb}}{^{86}\text{Sr}}$	$\frac{^{87}\text{Sr}}{^{86}\text{Sr}_{80}}$	Sr ppm
sediment	.70990		.70900	270
case 1				
mantle (1)	.70280	.007727	.702791	3.96
mix			.703378	4.36
Tro.av.			.703600	8.61
case 2				
mantle (2)	.702800	.005872	.702793	6.95
mix			.703610	8.00
Tro.av.			.703600	17.21

sediment and Troodos average (Tro.av.): see Table 8.7.

mantle (1),(2): uncontaminated mantle end member.

mix: mixtures between mantle (1),(2) and sediment.

Table 8.12. Pb isotopic ratios of uncontaminated mantle, sediment, calculated mixtures, and Troodos average.

	$\frac{^{206}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{207}\text{Pb}}{^{204}\text{Pb}}$	$\frac{^{208}\text{Pb}}{^{204}\text{Pb}}$	Pb ppm
sediment	18.762	15.658	38.847	25.40
case 1				
mantle (1)	18.400	15.480	37.900	.0236
mix	18.625	15.591	38.488	-
Tro.av.	18.625	15.570	38.484	-
case 2				
mantle (2)	18.400	15.480	37.900	.0394
mix	18.666	15.613	38.595	-
Tro.av.	18.625	15.570	38.484	-

sediment and Troodos average (Tro.av.): see Table 8.7.

mantle (1),(2): uncontaminated mantle end member.

mix: mixtures between mantle (1),(2) and sediment.

To obtain the concentrations of very incompatible trace elements in the mantle end member, the new REE patterns are extrapolated on an extended normalized concentration plot (Fig. 8.16, Table 8.10). This results in trace element patterns similar to those of N-MORB, but with a much stronger depletion of very incompatible elements. The extrapolation towards the very incompatible trace elements gives a mantle with $(\text{Cs/La})_N$ of 0.11 for case (1) and 0.09 for case (2). Both mantle end members are extremely depleted compared with N-MORB ($(\text{Cs/La})_N = 0.33$).

8.4.5 MIXTURE OF DEPLETED MANTLE AND SEDIMENT

For cases (1) and (2) the concentrations of very incompatible trace elements in a mixture between extrapolated mantle end member and sediment were calculated, and are compared with the trace element contents observed in the average of mafic Troodos glasses (Table 8.10 - 8.12, Fig. 8.16). The Sr and Pb isotopic compositions of the mixture were also determined. For the $^{87}\text{Sr}/^{86}\text{Sr}$ of the depleted mantle end member, the Sr isotopic ratio of N-MORB, age-corrected with the $^{87}\text{Rb}/^{86}\text{Sr}$ ratios of the extrapolated mantle end member was used. The age-correction for $^{87}\text{Sr}/^{86}\text{Sr}$ for the mantle end member is almost negligible, because the Rb concentration in the source is very low. Pb isotopic ratios were not age corrected.

The addition of sediment leads to a relative enrichment of LFS elements relative to REE, but is not satisfactory for all trace elements. The calculated abundances of Ba, Th, Nb agree well with the pattern observed in the average of mafic Troodos glasses, whereas the calculated concentrations of the more soluble elements Cs, Rb, K and Sr are significantly lower than the observed ones (Table 8.10, Fig. 8.16). The good fit of Ba, Th and Nb suggests that the concentrations of these elements are controlled by the addition of sediment to the depleted mantle. Even the negative Nb anomaly relative to the REE in the Troodos glasses, a feature observed in all island arc systems, can be explained by this mixing process. This suggests that this process may also be important for the generation of negative Nb anomalies in recent island arc systems. The calculated Pb isotopic ratios agree well with the range of values observed in the Troodos glasses. For one of the mixing calculations the average $^{87}\text{Sr}/^{86}\text{Sr}$ is balanced in the mixture, for the other one it is slightly too low. Also, the Sr concentrations

in the calculated mixture are lower than those observed in the Troodos lavas. A possible explanation for the slight misfit in $^{87}\text{Sr}/^{86}\text{Sr}$ is that the sediment had a more radiogenic Sr isotopic composition and had higher Sr concentrations than assumed for the calculations.

The observed and the calculated mixture compositions show good agreement for all elements and isotopic ratios, except for the water-soluble incompatible trace elements (Cs, Rb, K, Sr) and the variation in Sr isotopic composition.

8.4.6 HETEROGENEITY IN THE MANTLE WEDGE PRIOR TO CONTAMINATION

The previous calculations did not take into account the differences in REE concentrations, REE patterns, and ϵ_{Nd} of Troodos volcanics. Lavas with U-shaped REE patterns and very low ϵ_{Nd} are found in other areas of the Troodos ophiolite. Two glass samples (KA and LIM) with slightly different compositions from those of Akaki glasses were analyzed from other parts of the ophiolite (Fig. 1.2, 8.17). Sample LIM shows stronger positive La-Ce anomalies, is more depleted in REE (Fig. 4.22) and shows higher $^{87}\text{Sr}/^{86}\text{Sr}$, and Pb isotopic composition, and lower $^{143}\text{Nd}/^{144}\text{Nd}$. McCulloch and Cameron (1983) and Cameron (1985) described whole rock samples from the Arakapas area (southern part of the ophiolite) with extremely low ϵ_{Nd} of +0.7 and +1.7, and U-shaped REE pattern at low REE concentrations (Fig. 8.18, Table 8.13). These samples resemble boninites described from recent island arc environments (McCulloch & Cameron, 1983).

At a first glance, these volcanics seem to have an origin different from that of rocks described from the Akaki River section. However, mixing calculations similar to the ones described before can explain the observed compositions of the Arakapas area (Fig. 8.18, Table 8.13).

For the isotopic compositions of the depleted mantle end member, the one of N-MORB, age-corrected for 80 Ma, was used as in the calculations above. The relative and absolute trace element abundances were extrapolated. The HREE patterns of the Arakapas lavas were assumed to be parallel to those of the depleted mantle end member because in the mixing calculation above the HREE ratios were not significantly influenced by sediment addition. In contrast, the LREE

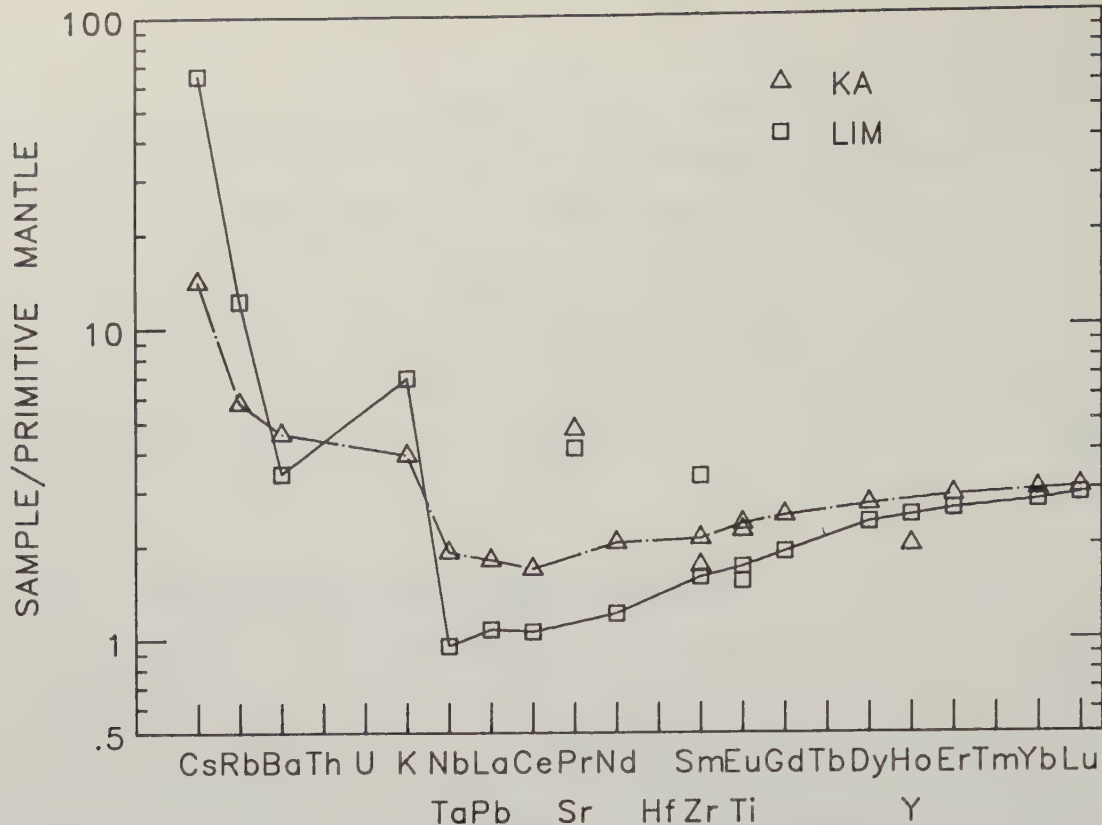


Fig. 8.17. Trace element concentrations of glasses KA and LIM from the Kalavassos and Limni area (normalized to primitive mantle).

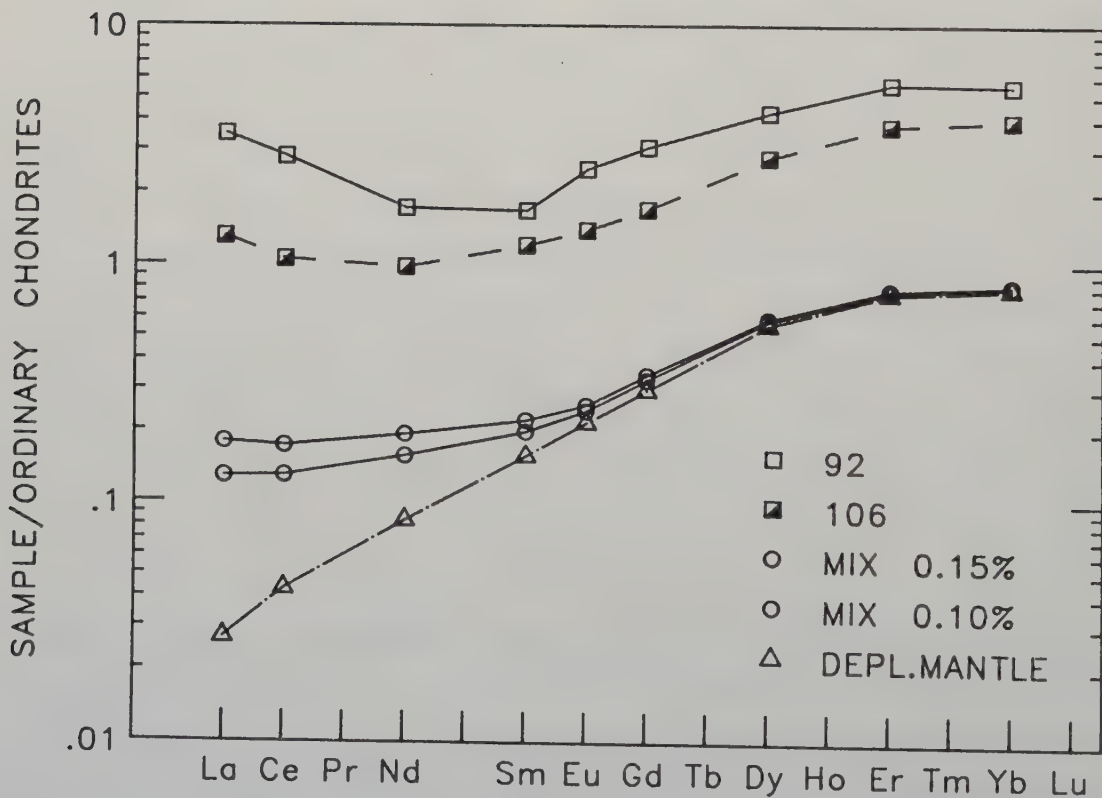


Fig. 8.18. REE concentrations (normalized to chondrites), of inferred Arakapas depleted mantle, extrapolated from 1/5 concentrations of sample 106 (triangles), mixtures of this mantle end member with 0.1% and 0.15% sediment (circles), and the volcanic samples 92 and 106 (McCulloch and Cameron, 1983) (Table 8.13).

Table 8.13. Compositions of extrapolated uncontaminated mantle (3) (Arakapas), calculated mixtures, and Arakapas lavas.

	mantle (3)	calculated mixtures		Arakapas lavas	
		+0.10% sediment	+0.15% sediment	92*	106*
La	.0085	.0404	.0563	1.09	0.72
Ce	.035	.105	.140	2.19	1.46
Nd	.050	.0933	.115	1.02	0.58
Sm	.030	.038	.0425	0.32	0.23
Eu	.0156	.0175	.0185	0.11	0.10
Gd	.077	.0851	.0893	0.80	0.44
Dy	.182	.189	.193	1.40	0.90
Er	.162	.166	.168	1.21	0.76
Yb	.166	.170	.172	1.40	0.84
$^{143}\text{Nd}/^{144}\text{Nd}$	.51296	.51264	.51257	.51262	.51257
$\epsilon_{\text{Nd}80}$	+8.3	+2.1	+0.7	+1.7	+0.7
$(\text{La}/\text{Yb})_{\text{N}}$	.0338				

mantle (3): LREE pattern and concentrations were extrapolated from HREE pattern, concentrations of HREE are 1/5 of those in sample 106.

mixtures: mixtures between mantle (3) and sediment.

Arakapas lavas*: McCulloch & Cameron (1983), Cameron (1985).

patterns were thought to be changed by the mixing process, as is also observed in the modelling of the Akaki glasses. Therefore the pattern indicated by Gd to Lu of one of the Arakapas lavas (sample 106) was extrapolated in a straight line to La. This results in a very LREE-depleted pattern with $(\text{La}/\text{Yb})_{\text{N}}$ of 0.034, compared to 0.318 and 0.263 for cases (1) and (2) in the modelling for the Akaki glasses (Table 8.13). The concentrations of the mantle end member were taken as one fifth of this extrapolated pattern, assuming 20% partial melting gave rise to the lavas. The sediment component used was the same as the one used in the earlier calculations (Table 8.7).

Mixing of this very depleted mantle end member with very small amounts (0.1%, 0.15%) of sediment reproduces not only the shape of the REE patterns of the Arakapas lavas, but also accounts for the drastic shift in ϵ_{Nd} from +8.3 in the depleted mantle to ϵ_{Nd} of +0.7 or +2 (Fig. 8.18, Table 8.13). This shows that a large shift in ϵ_{Nd} is not necessarily caused by a larger sediment contribution than in the modelling for the Akaki glasses (0.15% to 0.4%). On the contrary, if the mantle wedge is very depleted in LREE, a smaller addition of

sediment can cause the large shift of about seven epsilon units. Only with this type of mantle end member can the U-shaped REE pattern of the Arakapas lavas be obtained in a mixture of mantle and sediment. This process may also explain the chemistry of boninites found in recent fore-arc environments. The U-shaped REE patterns also support one of the initial assumptions, that the mixing occurred in the mantle source before partial melting. REE concentrations and REE patterns in a two-component mixture depend on the concentrations and patterns of REE and the proportions of the end members in the mixture. The larger the difference in REE pattern and concentration, the larger is the influence of the enriched end member (sediment) on the mixture. U-shaped REE patterns can only be generated if this difference is very large, e.g. if a very LREE-depleted Arakapas mantle (0.05 ppm Nd) is mixed with very LREE-enriched sediment (43 ppm Nd) (Fig. 8.18). Are the differences in concentrations smaller, e.g. if a LREE-depleted

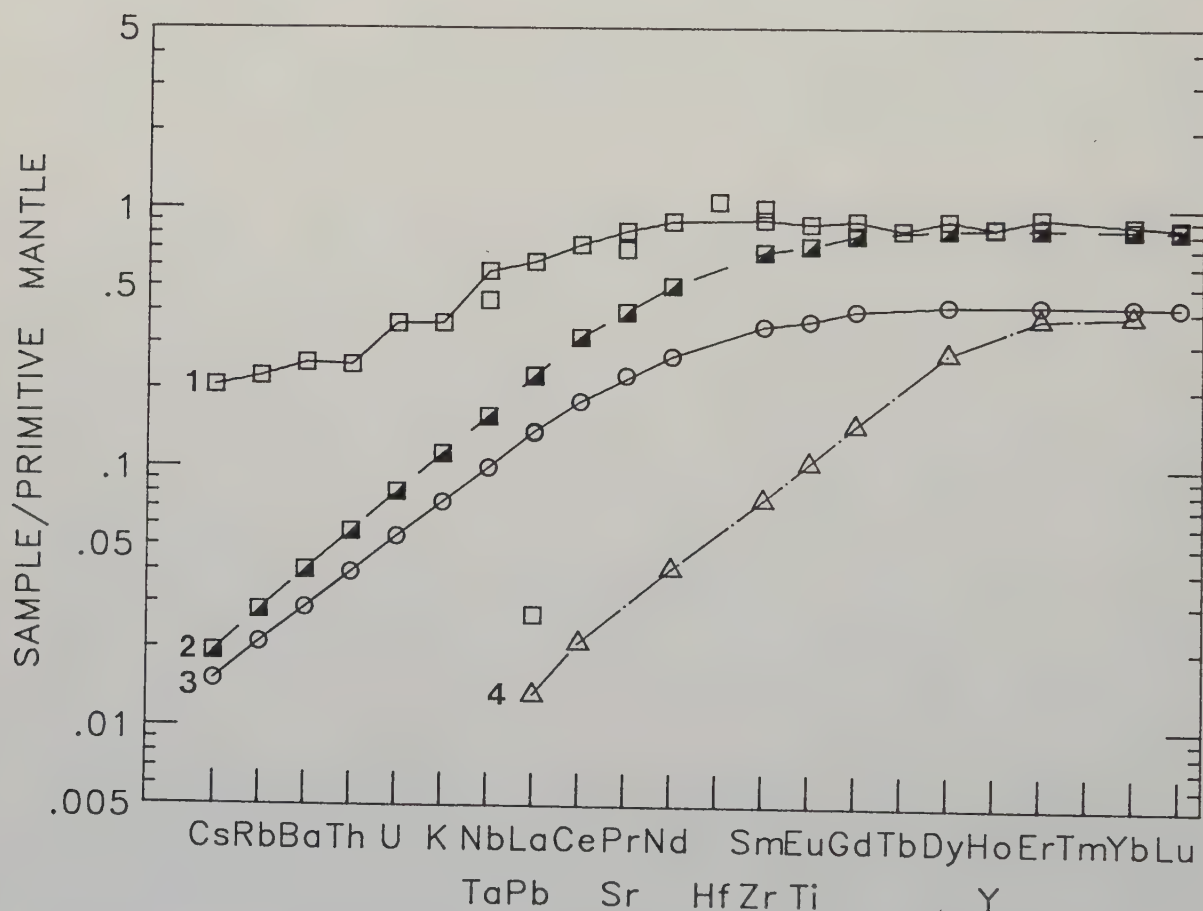


Fig. 8.19. The inferred compositions of the uncontaminated mantle end members used in the mixing calculations. Case (1) and (2) Akaki (Table 8.9, 8.10) and case (3) for the Arakapas mantle (Table 8.13). The N-MORB pattern (1/10 of the concentrations, Table 7.4) is shown for comparison.

Akaki mantle (0.4 ppm Nd) is mixed with LREE-enriched sediment (43 ppm Nd), this does not result in a U-shaped REE pattern, but in a flatter, but LREE-depleted pattern (Fig. 8.16). This means that if a magma with higher concentrations (e.g. 4 ppm Nd) is mixed with sediment, the difference in REE concentration and shape of REE patterns are even smaller and no U-shapes will be generated during mixing. This strongly suggests that mixing occurred in the mantle before partial melting gave rise to the Troodos magmas.

These model calculations suggest that a heterogeneous, variably depleted mantle end member was present beneath Troodos. With the addition of small amounts of sediment, this produced the observed mafic lava which range from boninitic to basaltic-andesitic. The inferred depleted mantle end members used in the model calculations are shown in Fig. 8.19. They are more LREE depleted than the N-MORB pattern, and the mantle end member used for modelling of the Arakapas lavas is even more depleted than that used for the Akaki glasses.

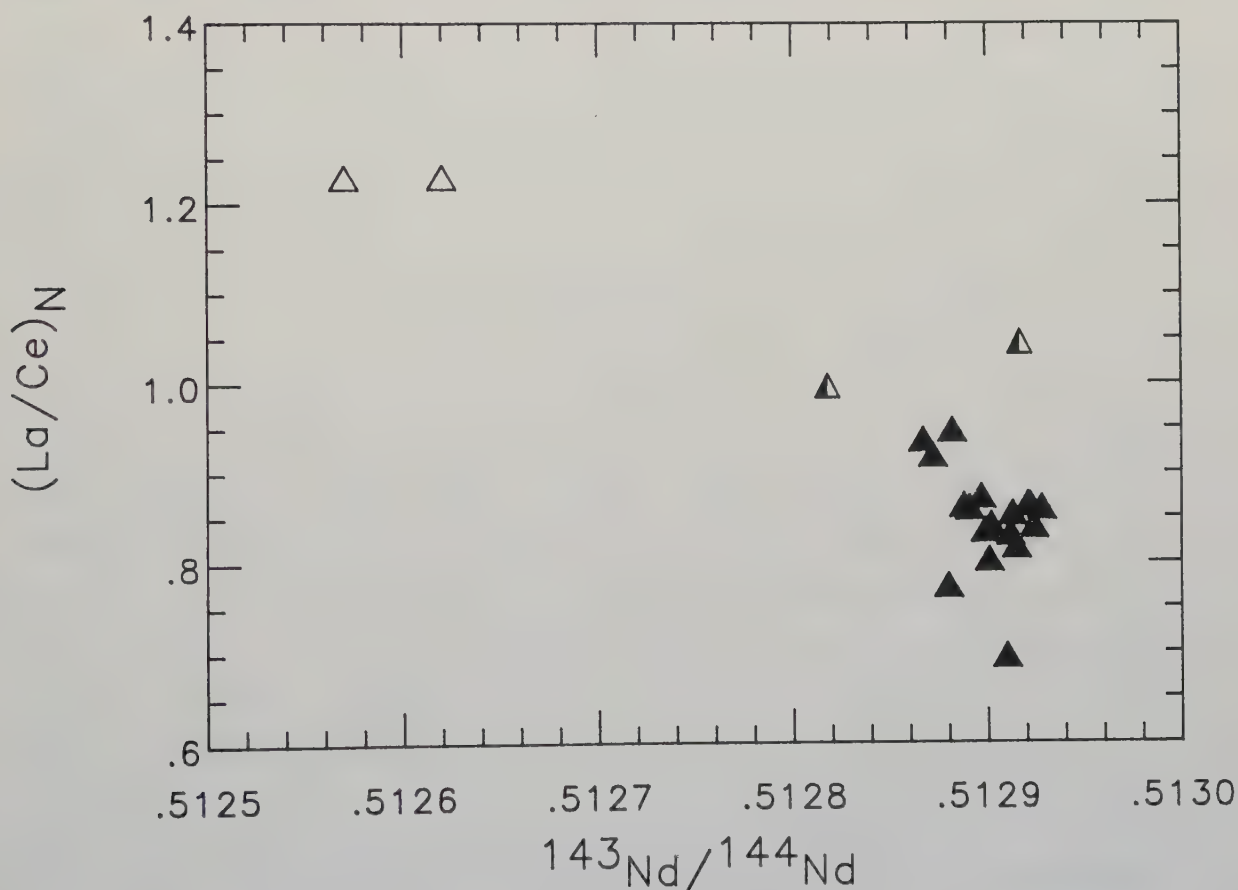


Fig. 8.20. $(La/Ce)_N$ versus $^{143}Nd/^{144}Nd$ for Akaki glasses (solid triangles), glass samples KA and LIM (half-filled triangles), and whole rock samples 92 and 106 from the Arakapas areas (open triangles) (McCulloch & Cameron, 1983).

For the case of the Akaki, the depleted mantle interacts with a small amount of sediment, causing a LREE-depleted REE pattern and a shift of the Nd isotopic ratio of two epsilon units in the mixture (Fig. 8.16). For a larger degree of LREE-depletion (as in the Arakapas mantle), a smaller amount of sediment is needed to cause a drastic shift of Nd isotopic ratio of seven epsilon units and a U-shaped REE pattern in the mixture (Fig. 8.18). The glass samples from Kalavassos and Limni (KA and LIM) and Akaki samples 315 and 345 are intermediate in their composition, showing REE patterns with small kinks in La and Ce and intermediate Nd isotopic ratios. This is also illustrated in Fig. 8.20, a plot of $(La/Ce)_N$ versus $^{143}Nd/^{144}Nd$. These data show a good negative correlation. Because the U-shaped REE patterns are most easily explained by interaction of an extremely LREE-depleted mantle with sediment, the $(La/Ce)_N$ ratio of the glasses gives an indication of the degree of LREE-depletion in the uncontaminated mantle end member. This suggests that there was a range of LREE-depletions present in the mantle wedge prior to contamination with subducted sediment from the subducted slab. It indicates that the degree of LREE-depletion in the depleted mantle was variable prior to contamination with sediment, possibly because of previous melting events, which gave rise to the basaltic magmas of oceanic crust. Thus, it is concluded that the mantle wedge was heterogeneous before contamination.

8.4.7 A THIRD COMPONENT IN THE MANTLE SOURCE?

Mixing between depleted mantle and sediment accounts for most of the characteristics of the Troodos lavas, but some discrepancies remain. $^{87}Sr/^{86}Sr$ in the Akaki glasses show a significant variation from 0.7031 to 0.7040, whereas the Nd and Pb isotopic ratios vary to a lesser extent (Fig. 7.8 - 7.10). Further, the water-soluble trace elements Cs, Rb, K, and Sr are higher in the glasses than expected from the mixing calculations (Fig. 8.16, Table 8.10 - 8.11).

The overabundance of these elements is also demonstrated in Fig. 8.21 where Rb/Ba ratios versus $^{87}Sr/^{86}Sr$ for Troodos glasses are shown. The sediment has a negative Rb anomaly relative to Cs and Ba when normalized to primitive mantle (Fig. 8.13, Table 8.7). Therefore, the Rb/Ba ratio of the sediment (0.056) is very similar to that of extrapolated, uncontaminated depleted mantle end member (0.065). On a diagram of Rb/Ba versus $^{87}Sr/^{86}Sr$ the mixing line between the two

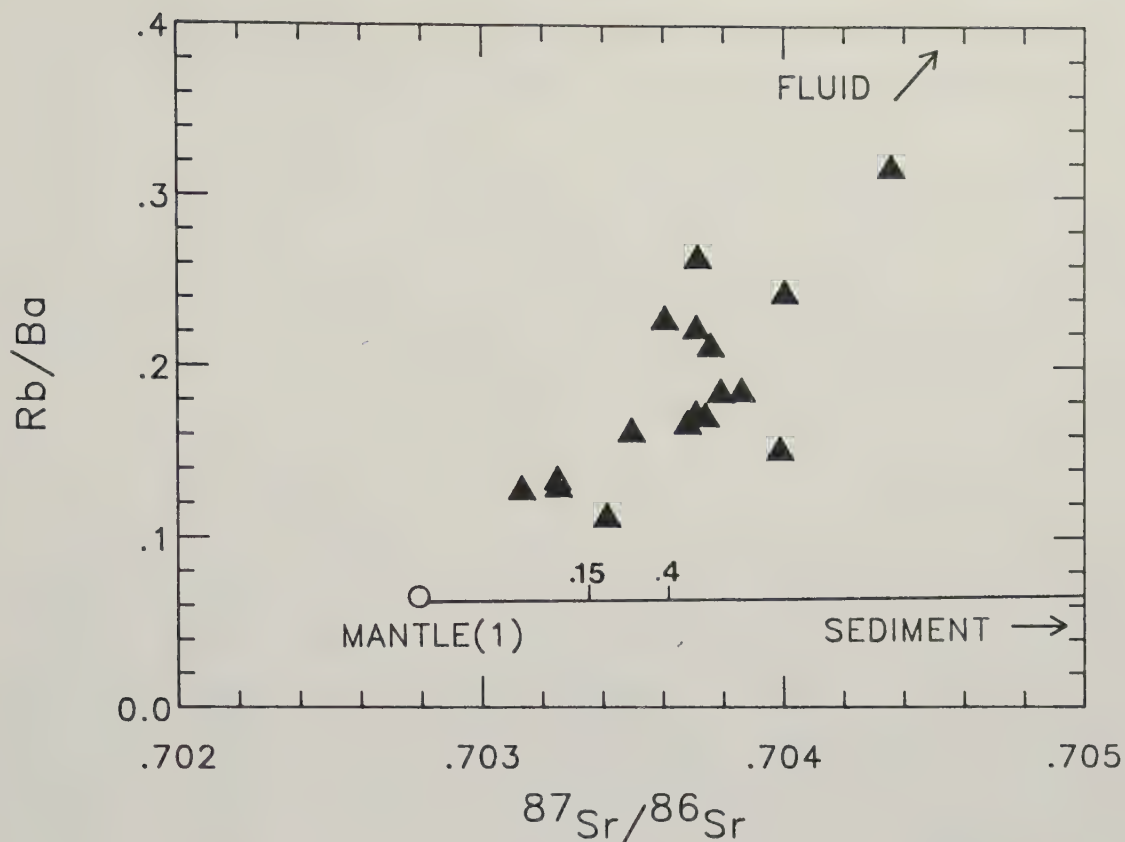


Fig. 8.21. Rb/Ba versus $^{86}\text{Sr}/^{87}\text{Sr}$ for depleted mantle (circle) and Troodos glasses (solid triangles). An arrow points towards the sediment composition. The mixtures of mantle and 0.15% or 0.4% sediment are shown on the mixing line between depleted mantle and sediment. Troodos glasses do not lie on this mixing line indicating that a third component is necessary to explain the chemistry of the glasses. This may be a soluble element rich fluid derived from the subducted slab.

reservoirs is therefore represented by a nearly horizontal straight line. However, the Rb/Ba ratios of the Troodos glasses are much higher and range from 0.1 to 0.32. Therefore these trace element ratios cannot be explained by mixing between sediment and depleted mantle. The ratios of Rb/Ba and $^{87}\text{Sr}/^{86}\text{Sr}$ are not changed during partial melting or fractional crystallization (see sections 8.2 and 8.3). The Ba and Th concentrations in the Troodos magmas were successfully modelled by mixing between depleted mantle and sediment. Therefore the variation in Rb/Ba (and Cs/Ba, K/Ba, and Sr/Ba) must be caused by a variable overabundance of Rb, Cs, K, and Sr. This suggests that there must be a third component in the mixing process to account for the higher concentrations of these elements and the variability in $^{87}\text{Sr}/^{86}\text{Sr}$.

This third component may be a hydrous fluid or a siliceous melt derived from dehydration or partial melting of the subducted oceanic lithosphere. If this component were a partial melt of the subducted lithosphere, it would contain high concentrations of all very incompatible elements, not only Cs, Rb, K, and Sr, but also Ba and Th. However only the more water-soluble elements are overabundant in the Troodos magmas. This suggests that the third component was a hydrous fluid derived by dehydration of the subducted slab, enriched in water-soluble trace elements and variable in $^{87}\text{Sr}/^{86}\text{Sr}$.

In summary, the trace element and isotopic compositions of the Troodos mantle source can be explained satisfactorily by a complex mixing interaction of three mantle components. A variably LREE-depleted mantle wedge was contaminated with variable, small amounts (0.1 to 0.4%) of subducted sediment, and a hydrous fluid component enriched in $^{87}\text{Sr}/^{86}\text{Sr}$ and water-soluble trace elements such as Cs, Rb, K, and Sr derived from dehydration of the subducted slab of oceanic lithosphere.

This complex mixing accounts for the heterogeneity in isotopic composition, the observed variation in incompatible elements, the different concentrations and patterns of REE, the variable enrichment of very incompatible elements, and at least in part for the negative Nb anomalies relative to the REE. The mixing has no significant effect on the composition of the major elements, because the amounts of sediment and fluid are too small and because the major element chemistry is much more strongly buffered by the residual mineral assemblage than is the incompatible element chemistry.

8.5 SUMMARY OF PROCESSES OPERATING

Several processes contributed to the generation of the Troodos magmas and led to the observed range of chemical compositions of the volcanics.

The results of the quantitative modelling for major elements are consistent with fractional crystallization of an ol-cpx-plag or a opx-cpx-plag assemblage. If these results are applied to the trace element compositions of the lavas, some trace element ratios, e.g. the REE patterns can be reproduced, but the absolute concentrations of trace

elements do not agree. The variation in other trace element ratios such as Rb/Ba cannot be explained by fractional crystallization.

Different degrees of partial melting may have generated several magmas with different concentrations but nearly constant ratios of incompatible trace elements. This may explain the difference in incompatible trace elements in the mafic Troodos lavas. Neither partial melting nor fractional crystallization can explain the variation of very incompatible trace element ratios such as Rb/Ba or the heterogeneous isotopic compositions.

The chemical compositions of the Troodos lavas are consistent with a complex three component mixing process in the mantle source prior to partial melting. One component is a variably depleted mantle, presumably depleted by previous melting events, the second is a subducted sediment, and the third is a hydrous fluid phase, enriched in $^{87}\text{Sr}/^{86}\text{Sr}$ and soluble trace elements such as Cs, Rb, K, and Sr derived by dehydration of the subducted oceanic lithosphere. This complex mixing accounts for the heterogeneity in isotopic composition, and the observed range in incompatible trace element concentrations and ratios, and also may account for boninite-type lavas such as described from the Arakapas area by McCulloch & Cameron (1983).

CHAPTER 9. CONCLUSIONS

The aim of this study was to characterize the processes that operated during the formation of the volcanics of the Troodos ophiolite. Two aspects were studied in detail, the volcanology of the lavas and their chemical composition.

Field data from the Akaki River section set constraints about volcanic processes operating at the sea floor for the Troodos ophiolite, and may have implications for recent submarine volcanics. Several extrusive lithologic types, pillow lavas, sheet flows, large lava tubes, large irregular bodies, several types of breccias, and intrusive types such as dikes and sills were distinguished. The subdivision of the Akaki River into 12 stratigraphic units was based on the occurrence and characteristics of extrusive lithologic types. One or several of these stratigraphic units represent a cross section through a volcano. These volcanoes have a elongated shapes, they are about 100 - 300 m high, up to 800 m wide, and probably up to 1600 m long.

A cyclic constructional model for the evolution of the Troodos submarine volcanos was developed. It comprises the following stages: (1) the sheet flow stage (high eruption rates); (2) the formation of the feeding system consisting of large irregular bodies, large tubes, and pillowed lavas (starting at low, then slowly increasing eruption rates); (3) the formation of the main pillowed part (at a rather constant eruption rate); (4) the end of the eruption cycle, formation of miniature pillows and extrusive breccias (at low eruption rates).

The typical succession of sheet flows, large lava bodies, large tubes and pillow lavas found in the Troodos volcanics is also described from modern oceanic ridges. It is therefore suggested that the mode of construction proposed for the volcanic edifices of the Troodos ophiolite may also be applicable for volcanos at oceanic ridges today.

Detailed mapping facilitated the collection of a well documented

representative suite of fresh volcanic glasses and whole rock samples for analysis. The freshness of the glasses made the preparation of clean glass separates possible, and these were analyzed with high precision methods for isotopic compositions, major and trace elements.

The glass compositions are interpreted to be fresh even for the most alteration-sensitive trace elements and isotopic ratios. The quality of this data set permitted a comparison of the Troodos ophiolite with recent volcanics from constructive and destructive margins also with respect to the alteration-sensitive elements and to draw constraints about the origin of the Troodos volcanics.

The major, trace element and isotopic characteristics of the Troodos glasses, including their volatile content, are similar to those found in supra-subduction zone volcanics. For the first time in the study of the Troodos volcanics, it has been possible to extend the comparison with modern volcanics for the alteration-sensitive LFS elements. As a result, an origin at a major ocean basin spreading ridge is precluded, at least to the extent that any such conclusion can be drawn from chemical evidence. Comparison of the geological and geochemical evidence from Troodos and that from supra-subduction zone environments today suggest that the Troodos ophiolite formed in the earliest stages of island arc development rather than in a back arc basin environment.

The freshness of the glasses permitted to constrain the processes operating in the generation of the Troodos magmas. The observed range of chemical compositions of the glasses suggests that the Troodos magma source is heterogeneous.

The trace element and isotopic compositions, e.g the high Pb and low Nd isotopic ratios of the Troodos volcanics can be convincingly explained by mixing of mantle components from a subduction zone environment, namely a variably depleted mantle end member and subducted sediment. Differences in LFS element ratios such as Ba/Rb are observed in the glasses and cannot be accounted for with a simple two component

mixing model. They indicate the presence of a third component in the mantle source. This is presumably a water-soluble element-rich fluid phase derived from dehydration of the subducted slab.

It is very difficult to envisage an interaction of these components in any other than a subduction zone related environment. The evidence for a sedimentary component in the mantle source is compelling. It may not be justified to exclude a MORB origin for the Troodos glasses only on the basis of an empiric comparison with recent oceanic volcanics, but the presence of a sedimentary component in the Troodos mantle source and the lack of a sedimentary signature in any MORB strongly support that conclusion.

In conclusion, this "classical" ophiolite complex did not form at a normal oceanic spreading ridge, but was generated by complex processes operating in a subduction zone environment. This may be true for other ophiolites as well and should be taken into consideration before conclusions about processes in the generation of modern oceanic crust are drawn from ophiolites.

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Table A.1 Sample description

sample	strat. unit	strat. depth (m)	rock type	analyzed	chem. type
30	A	15	pillow rim	WR	B
31	A	15	pillow rim	WR	BA
33	A	20	pillow center	WR	B
35	A	40	pillow rim	WR	BA
36	A	40	pillow center	WR	BA
38	A	90	pillow rim	WR	B
39	A	90	pillow center	WR	B
42	A	95	tube center	WR	BA
43	A	95	tube rim	WR	BA
45	A	87	dike	WR	BA
46	A	85	dike	WR	B
47	A	128	large body	WR	BA
49	A	128	pillow rim	WR	BA
50	A	128	pillow center	WR	BA
51	B	190	pillow rim	WR	B
53	B	190	pillow center	WR	B
58	B	250	pillow center	WR	B
60	A	115	tube rim	WR	B
61	A	115	tube rim	WR	A
62	A	120	tube rim	WR	A
63	A	120	tube rim	WR	B
65*	A	140	pillow rim	G; WR	BA
67	A	140	tube rim	WR	B
68	A	140	tube center	WR	BA
69	A	140	pillow rim	WR	A
70	A	140	dike	WR	BA
71	B	170	pillow rim	WR	B
74	B	210	pillow center	WR	B
78	C	280	dike rim	WR	BA
79	C	280	dike rim	WR	BA
80	C	280	dike rim	WR	A
81	C	275	sheet flow base	WR	A
82	C	275	sheet flow top	WR	A
84	B	265	pillow center	WR	B
85	B	265	pillow rim	WR	BA
87*	B	260	pillow rim	G, WR	BA
88	B	260	pillow rim	WR	BA
89	B	260	pillow center	WR	B
90	C	279	sheet flow base	WR	A
91	C	279	sheet flow center	WR	A
93	C	275	sheet flow base	WR	A
94	C	289	sheet flow base	WR	A
96	B	275	dike center	WR	BA
97	B	289	sheet flow center	WR	D
98	C	282	dike rim	WR	A
99/	C	282	dike rim	G, WR	A
100	C	282	dike center	WR	BA
103	C	282	dike center	WR	BA
104	C	282	dike rim	WR	A
105	C	292	dike	WR	BA
106	D	380	pillow center	WR	BA
107	D	380	pillow rim	WR	B
110	D	365	pillow center	WR	BA
111	D	365	pillow	WR	BA
114	D	400	pillow center	WR	B
117	D	435	large body	WR	B

120	E	440	pillow center	WR	B
122	E	490	pillow rim	WR	B
126	E	554	dike center	WR	A
129	E	565	sheet flow base	WR	BA
130	E	570	pillow center	WR	BA
131	E	570	pillow rim	WR	BA
132	E	572	sheet flow center	WR	BA
133	E	570	sheet flwo center	WR	BA
135	E	570	dike rim	WR	B
139	F	660	large body	WR	BA
142	F	670	pillow center	WR	BA
144	F	670	pillow rim	WR	A
145	F	750	large body	WR	BA
149	F	740	dike center	WR	B
152	F	735	tube rim	WR	BA
154	F	735	pillow center	WR	BA
160	F	810	tube center	WR	BA
163*	F	805	tube rim	G, WR	BA
165	F	720	pillow rim	WR	BA
171	G	830	pillow center	WR	BA
172	G	830	pillow rim	WR	BA
173	G	830	pillow rim	WR	A
177	G	850	sheet flow	WR	A
180	G	850	pillow rim	WR	BA
181	G	850	pillow	WR	
190	H	900	pillow center	WR	A
191	H	900	pillow center	WR	A
192	H	900	pillow rim	WR	A
193	H	925	pillow center	WR	BA
194	H	925	pillow rim	WR	BA
200	I	965	dike center	WR	B
204	I	1010	sheet flow center	WR	BA
205*	I	1010	sheet flow	G, WR	A
213	J	1050	pillow center	WR	A
214*	J	1050	pillow rim	G, WR	A
221	J	1125	tube center	WR	BA
233	K	1300	pillow rim	WR	BA
235	K	1300	pillow center	WR	D
237*	K	1300	pillow rim	G, WR	A
242*	K	1340	pillow center	G, WR	A
245	L	1520	pillow rim	WR	BA
246	K	1410	pillow rim	WR	D
248	L	1530	sheet flow center	WR	A
249*	L	1480	dike center	G, WR	BA
256/	L	1525	dike center	G, WR	D
258/	L	1525	dike rim	G, WR	D
259	L	1550	pillow center	WR	A
262*	L	1585	pillow center	G, WR	BA
305	A	100	large body	GS, WR	BA
306*	A	130	tube rim	G, WR	BA
310*	C	275	sheet flow	G, WR	BA
310/	C	275	dike	G, WR	BA
311/	C	282	dike rim	G, WR	BA
312/	C	282	dike rim	G, WR	A
313	C	285	sheet flow	GS, WR	A
314/	C	285	dike	G, WR	A
315	C	292	dike rim	GS, WR	BA
316	C	275	feeder dike	GS, WR, AG	BA
317*	C	275	sheet flow	G, WR	BA
318*	C	281	sheet flow	G, WR	A
320/	C	280	dike	G, WR	A

321/	C	280	dike rim	G, WR	BA
323*	B	260	pillow rim	G, WR	BA
324.1*	B	265	pillow rim	G, WR	BA
324.2*	B	265	pillow rim	G, WR	BA
325	B	265	pillow rim	WR	BA
326*	B	265	pillow rim	G, WR	BA
331	G	845	sheet flow	GS, WR	A
335*	J	1070	sheet flow	G, WR	A
336	K	1300	hyaloclastite	GS, WR, AG	A
336B*	K	1300	hyaloclastite	G, WR	A
340	A	130	tube rim	GS, WR	BA
341.1*	B	190	pillow rim	G, WR	BA
341.2*	B	190	pillow rim	G, WR	BA
343	E	575	sheet flow	GS, WR	B
345	E	550	dike rim	GS, WR, AG	A
346	E	550	dike rim	GS, WR	A
350	F	790	pillow rim	GS, WR	BA
353	L	1520	hyaloclastite	GS, WR	D
362*	H	900	hyaloclastite	G, WR	A
363	H	925	pillow rim	GS, WR	A
368	I	965	hyaloclastite	GS, WR	A
369*	H	930	pillow	G, WR	BA
370	I	1015	sheet flow	GS, WR	A
371	J	1065	pillow rim	GS, WR, AG	A
372	F	745	pillow center	WR	BA
373	F	740	pillow rim	WR	BA
374	F	730	pillow rim	WR	BA
375	F	720	pillow center	WR	BA
376	F	720	pillow center	WR	BA
377	F	710	pillow center	WR	BA
378	F	690	pillow center	WR	B
379	F	690	pillow center	WR	B
380	F	685	pillow center	WR	BA
381	F	685	pillow center	WR	BA
402*	E	500	sheet flow	G, WR	A
403	E	510	dike	WR	BA
404	E	510	tube	WR	BA
405	E	505	dike	WR	A
406*	F	790	large body	G, WR	A
410	F	790	dike	WR	BA
412/	F	740	dike	G, WR	A
414	F	735	dike	WR	BA
415	F	745	dike	GS, WR	A
420	A	10	pillow center	WR	B
421	A	20	pillow center	WR	B
422	A	30	pillow	WR	BA
423	A	40	pillow	WR	BA
424	A	50	pillow	WR	BA
425	A	70	pillow	WR	B
426	A	80	pillow	WR	BA
427	A	90	pillow	WR	B
428	K	1400	dike	WR	BA
429	K	1400	dike	WR	BA
431	E	551	sheet flow	WR	A
432	E	550	sheet flow	WR	BA
433	E	549	sheet flow	WR	BA
434	E	545	sheet flow	WR	A
435*	E	545	sheet flow	G, WR	A
436	E	543	sheet flow	WR	BA
437	E	540	sheet flow	WR	BA
439	E	550	sheet flow	WR	A

440	E	555	sheet flow	WR	BA
441	F	745	tube	WR	BA
442	F	745	tube	WR	BA
443	F	745	tube	WR	BA
444	F	745	tube	WR	BA
445	F	745	tube	WR	BA
446	F	745	tube	WR	BA
447	F	745	tube	WR	BA
448	F	745	tube	WR	BA
450	G	845	sheet flow	WR	BA
451	G	845	sheet flow	WR	A
454	G	855	tube center	WR	BA
455	B	190	pillow	WR	B
461	F	745	pillow	WR	BA
465	F	745	large body	WR	BA
468	F	745	large body	WR	BA
469	F	690	dike	WR	A
470	F	690	dike	WR	BA
471	F	690	dike	WR	BA
473	F	690	dike	WR	BA
474	F	690	dike	WR	A
479	F	693	large body	WR	BA
483	F	690	dike	WR	BA
484	F	770	dike	WR	BA
486	I	965	dike	WR	
487	I	945	sheet flow	WR	BA
488	I	955	sheet flow	WR	A
489	I	980	dike	WR	BA
492	J	940	dike	WR	BA
496	J	940	dike	WR	
498*	K	1480	hyaloclastite	G, WR	A
500	K	1530	pillow	GS, WR, AG	A
503	K	1300	dike	WR	BA
504	K	1450	dike	WR	A
506	L	1950	dike	WR	BA
507	L	1950	pillow	WR	A
509	L	1950	pillow	WR	BA
516*	K	1490	hyaloclastite	G, WR	D
518E*	K	1510	hyaloclastite	G, WR	D
518I/	K	1510	dike	G, WR	D
521	K	1520	dike	WR	
523	K	1520	dike	WR	D
524	K	1520	pillow	WR	
526	L	1500	pillow	WR	
527	L	1500	dike	WR	A
529	L	1450	sheet flow	WR	
530	L	1450	pillow	WR	
534/	K	1400	large body	G, WR	A
537	A	130	tube	WR	B
539	C	275	sheet flow	WR	
540	C	275	sheet flow	WR	
541	C	275	sheet flow	WR	
542	C	290	sheet flow	WR	A
544	D	385	pillow	GS, WR	B
KA	Kalavasos		pillow	GS, WR	BA
LIM	Limni		pillow	GS, WR	A

B: basalt, BA: basaltic andesite, A: andesite, D: dacite
G: glass, GS: glass separate, WR: whole rock, AG: altered glass

Legend for Table A.2.

Phenocrysts:

e euhedral
s subhedral
a anhedral
g glomerophenocryst
z zoned,
sk skeletal
p pseudomorphs

grdm.gl: groundmass glass (originally present)

alt.: Alteration

0-2% f fresh
2-10% sl slightly
10-40% m moderately
40-80% s strongly
80-90% vs very strongly
90-100% c completely

Secondary minerals:

cl clay
cc carbonate
chl chlorite
zeo zeolite
ce celadonite
qtz quartz
p palagonite

a)

Table A.2 Petrographic description of thin sections

sample	olivine			cpx			plagioclase			spinel		
	%	mm	shape	%	mm	shape	%	mm	shape	%	mm	shape
30												
31												
33	15	1.0-8.0	s	1-2	0.6-2.4	e				<1	0.6	e
36				<1	0.3	s	<1	0.3	a			
38												
45	25	2.0-7.0	e-s	<1	1.0	e				<1	0.1-0.3	e
46	30	2.0-10.0	e							<1	0.5	s-e
47												
49	<1	0.5	e,p	4	0.2	e,g	4	0.2	e,g			
50				<1	0.3	e,g						
51	3	1.0-1.8	s,p	5	1.0	e,z						
53	3	1.2	e,sk,p	5	0.2-0.6	e,z,g						
58	1	0.8-1.2	e,sk,p	3	0.8-1.0	e,z						
60				<1	0.3	s	<1	0.4	s			
61				<1	0.3	s						
62				<<1	0.3	e-s						
63				<1	0.5	e-s,z	<<1	0.3	a			
67				<<1	0.4	s						
68				<1	0.3-0.5	s,g	<1	0.6-1.0	s-a			
70	20	2.4-10.0	s,p	<1	0.6	s				1	0.1	e
78												
85	1	0.6-0.8	s,p	3	0.3-0.6	e,z,g	1	0.3	s,z,g			
88	<1	0.5	s,p	2	0.6	e,g	<1	0.3	s,g			
89	<1	1.0	s,p	2	0.6-1.0	e,z,g						
96				<<1	0.6	e-s	<<1	0.9	s			
98												
100				<<1	0.5	e-s						
103				1	0.6	e-s	<<1	0.4	a			
114	1	0.6-1.0	e,sk,p	1	0.4	s,g	1	0.5	s,g			
120	3	1.0-1.5	sk,p									
126							<1	0.4	e-s,z			
129				1	0.6	s,g	1	0.6	a,g			
132				<<1	0.6	s,g	<<1	0.2	a,g			
133				1	0.3-0.6	s						
135				1	0.5	s	<1	0.9	s,z			
139				<1	0.6	e	<1	0.6	s			
142												
145												
149	20	0.4-1.4	e-s	1	0.3-0.6	e-s,g						
152												
160				<1	0.3	s,z	1	0.3-0.4	s-e,z			
165	1	0.9	s,p	<1	0.3	e						
171												
172				1	0.3	s-e						
177												
181												
190												
191												
192												
193												
194												
200												
204												
213												
221												
233												
235												
245												
246												
248												
249	1	2.4	s,p	1	0.3-0.9	e						
256	3	0.3	s,p									
259							<<1	0.6	e			
262							<<1	0.6	e			
305				<1	0.3	e,s						
313												
315				<<1	0.3	e	<<1	0.3	s-e			
316	<1	0.2	s	1	0.3	e-s	<<1	0.2	s-e			
331	<<1	0.2	s-e	<<1	0.3	e-s	<<1	0.3	s-e			
336				<<1	0.2	e	<<1	0.2	e			
340												
341	<1	0.3	e	<1	0.3	s						
345				<1	0.2	e-s	<<1	0.2	e-s			
346				<1	0.2	e-s						
350				<1	0.3	e-s	<<1	0.3	e			
353				<<1	0.3	e	<<1	0.2	e			
363							<1	0.2	e			
368				<<1	0.2	e-s	<<1	0.4	e-s			
370							<1	0.1	e			
371	<<1	0.2	e	<<1	0.3	e						
498				<1	opx		<1	0.6	e-s			
KA	1	1-2	e,sk									
LIM	<1	0.5	e	1	opx							

b)

Table A.2 Petrographic description of thin sections

sample	groundmass cpx		groundmass plag		groundmass opa.		grdm.gl	alt.	sec.min.	vesicles
	%	mm	%	mm	%	mm	%			%
30										
31										
33	15	<0.7	15	<0.07	2	<0.03	50	s	cl,cc,chl	2
36								c	cl	
38	3	0.1	5	0.15			92	vs	cl	
45	30	<0.1	21	0.1	1	0.03	21	m	cl	
46	26	<0.1	22	0.1	1	<0.03	20	m	cl	
47	30	0.15	50	0.5	1	0.03	19	m	cl,ce	3
49							92	s	cl	<1
50	30	<0.07	40	<0.1			20	m	cl	2
51	35	<0.07	17	0.12	<1	<0.03	40	s	cl,cc	8
53	35	<0.1	17	<0.1			40	s	cl,cc	5
58	30	<0.1	30	<0.1			36	m	cl,cc,ce	3
60	30	<0.1	30	<0.1			39	s	cl,cc,zeo	5
61	30	<0.1	40	<0.1	2	0.03	28	m	cl,cc	1
62	25	<0.1	30	<0.1	5	<0.02	40	m	cl	3
63	35	<0.1	35	<0.1	1	<0.03	29	sl	cl	3
67	30	<0.1	40	<0.1	1	<0.03	30	m	cl	5
68	30	0.3	45	0.4	1	0.03	24	m	cl	
70	30	<0.1	20	.08	2	<0.1	18	s	cl,cc	3
78	20	0.08	38	0.14	2	<0.03	40	m	cl	
85							95	s	cl	
88	10	<0.1	10	<0.1	1	<0.03	77	m	cl	5
89	35	<0.1	27	0.15	1	<0.03	35	m	cl	1
96	30	<0.1	30	<0.1	1	<0.03	39	s	cl	3
98								c	cl	
100	40	0.1	40	0.14			20	s	cl	
103	25	<0.1	25	<0.1	<1	<0.03	50	vs	cl	
114	10	<0.1	10	<0.1			78	vs	cl	2
120	23	<0.1	23	<0.1	1	<0.03	50	s	cl,zeo	<1
126	30	<0.1	50	<0.2	1	<0.05	9	s	cl	1
129	30	0.2	40	<0.4	1	<0.07	27	s	cl,zeo,ce	3
132	19	0.14	40	0.2	1	<0.05	40	vs	cl,zeo,ce	<1
133	30	0.1	50	0.2	1	<0.07	19	m	cl,zeo,ce,	1
135	20	<0.1	40	<0.2	1	<0.1	39	c	cl	
139	35	<0.3	45	0.3	1	<0.1	18	s	cl	1
142	10	<0.1	20	0.1	1	<0.03	69	s	cl	
145	40	0.3	50	0.5	1	<0.07	9	m	cl	
149	35	0.8	25	<0.2	<1	<0.03	20	m	cl,zeo,chl	1
152	25	<0.1	35	0.2	2	<0.1	40	m	cl,cc,zeo	3
160	20	0.15	50	0.2	2	<0.03	28	s	cl,zeo	1
165	10	<0.1	10	<0.1	1	<0.03	79	s	cl,cc,zeo	5
171	20	0.2	10	0.2			70	m	cl	<1
172	50	<0.01					49	sl	cl	3
177	20	<0.1	20	<0.1	<1	<0.03	60	sl	cl	5
181	10	<0.2	10	<0.07			74	sl	cl	1
190							100	c	cl,cc,zeo	
191	30	<0.07	30	<0.07	<1	<0.03	39	vs	cl,qtz,cc	2
192	30	<0.07	20	<0.07			50	vs	cl,cc,qtz	1
193	20	<0.1	25	<0.1			55	m	cl,cc,zeo	1
194	15	<0.1	30	<0.1			55	m	cl,cc	
200	10	<0.07	35	0.2	<<1	<0.03	55	m	cl	
204	30	0.08	20	0.7	1	<0.03	50	m	cl,chl,qtz	1
213	15	0.08	10	0.2	<<1		75	s	cl,cc	1
221	30	0.2	25	0.4	2	<0.03	33	m	cl	
233							70	s	cl,zeo,chl	3
235	10	<0.07	30	0.08	3	0.03	57	m	cl	15
245							100	c	cl,chl,qtz	1
246	15	<0.07	30	0.07	2	<0.03	53	c	cl,qtz	1
248			30	0.1	3	<0.03	67	vs	cl,qtz,chl	1
249	30	0.8	30	0.8	1	<0.07	27	s	cl,cc,chl,q	2
256	10	<0.05	10	<0.05			77	vs	cl	
259	5	<0.07	35	0.8	2	<0.03	53	s	cl,zeo	3
262	20	0.08	30	0.08	2	<0.03	48	c	cl,qtz,zeo,	2
305							>99	f	p	
313							100	f	p	
315							>99	f	p	
316							99	f	p	
331							>99	f	p	
336							>99	f	p	
340							100	f	p	
341							>99	f	p	
345							>99	f	p	1
346							>99	f	p	3
350							100	f	p	
353							>99	f	p	
363							>99	f	p	
368							>99	f	p	
370							>99	f	p	3
371							>99	f	p	1
498							100	f	p	
KA							99	f		
LIM							99	f		

Table A.3 Standard determined with microprobe,
Memorial University

	ACPX		
	meas.	std.dev.	recomm.
SiO ₂	50.24	0.24	50.73
TiO ₂	0.79	0.04	0.74
Al ₂ O ₃	7.74	0.09	7.86
FeO	6.22	0.09	6.77
MnO	0.15	0.03	0.13
MgO	16.33	0.38	16.65
CaO	15.80	0.28	15.82
Na ₂ O	1.29	0.10	1.27
K ₂ O	0.01	0.01	
Cr ₂ O ₃	0.15	0.02	
NiO	0.05	0.01	

Table A.4 Standards determined with XRF at Ruhr-Universität Bochum

	ANG		BEN	
	recomm.	meas.	recomm.	meas.
SiO ₂	46.30	46.70	38.20	38.50
TiO ₂	0.22	0.23	2.61	2.65
Al ₂ O ₃	29.80	29.86	10.07	10.07
Fe ₂ O ₃	3.34	3.33	12.84	12.82
MnO	0.04	0.05	0.20	0.20
MgO	1.80	1.75	13.15	13.32
CaO	15.90	16.06	13.87	13.92
Na ₂ O	1.63	1.55	3.18	2.95
K ₂ O	0.13	0.13	1.39	1.35
P ₂ O ₅	0.01	0.02	1.05	1.04
Rb	1	1	48	47
Sr	79	78	1370	1421
Ba	34	<10	1025	1061
Zr	15	13	263	213
Y	8	8	30	28
Cr	50	46	360	346
Co	25	18	61	57
Ni	35	45	267	262

	BR*	
	recomm.	meas.
SiO ₂	38.40	38.60
TiO ₂	2.61	2.67
Al ₂ O ₃	10.25	10.08
Fe ₂ O ₃	12.92	12.90
MnO	0.20	0.20
MgO	13.35	13.38
CaO	13.87	13.61
Na ₂ O	3.07	2.99
K ₂ O	1.41	1.41
P ₂ O ₅	1.05	1.06
Rb	47	47
Sr	1320	1372
Ba	1050	1372
Zr	250	255
Y	30	31
Cr	380	357
Co	50	68
Ni	260	283

* is used in the calibration curve.
recomm.: Gowindaraju (1984)

Table A.5 Standards determined with XRF at Memorial University

	BCR		WI	
	meas.	recomm.	meas.	recomm.
Rb	48	47	22	21
Sr	332	330	180	190
Zr	188	185	86	95
Nb	13.2	13.5	7.5	9.0
Y	34	38	19	25

	AGV		BHVO	
	meas.	recomm.	meas.	recomm.
Rb	68	67	10	10
Sr	658	660	378	396
Zr	224	230	160	170
Nb	12.5	14.0	17.8	19.0
Y	14	20	23	28

measured Y results were adjusted to +20% to obtain BCR and BHVO as accepted values. recomm.; Flanagan (1976).

Table A.6. Zr concentrations determined with XRF at Ruhr-Universität Bochum and Memorial Univerity, Newfoundland.

sample	Zr XRF Bochum 1983	Zr XRF Bochum 1986	Zr XRF Memorial 1986
31	42		32
111	46		35
233	65		60
259	65		59
316	40	39	29
340	43	45	34
345	30	31	22
353	94	98	85
363	47	47	37
370	60	61	48
371	47	49	37

Table A.7 Standards determined with AA at Memorial University

standard	GSP-1 recomm.	n	mean meas.	std.dev.
SiO ₂	62.17	7	68.65	0.60
TiO ₂	0.65	7	0.60	0.08
Al ₂ O ₃	15.18	7	14.77	0.22
Fe ₂ O ₃	4.26	8	4.22	0.07
MnO	0.04	8	0.04	0.01
MgO	0.98	7	0.96	0.03
CaO	2.06	8	1.94	0.07
Na ₂ O	2.77	8	2.74	0.06
K ₂ O	5.50	6	5.44	0.12
Cr\$	12.5	4	11.0	1.3
Ni\$	12.5	5	41.0	7.5

standard	AGV-1 recomm.	n	mean meas.	std.dev.
SiO ₂	58.97	3	59.63	0.90
TiO ₂	1.06	3	1.08	0.11
Al ₂ O ₃	17.01	4	17.13	0.23
Fe ₂ O ₃	6.73	4	6.70	0.33
MnO	0.10	4	0.10	0.00
MgO	1.53	4	1.47	0.07
CaO	4.94	4	4.78	0.16
Na ₂ O	4.26	4	4.06	0.12
K ₂ O	2.86	3	2.88	0.10
Cr\$	12.2	4	12.0	1.8
Ni\$	18.5	5	51.0	4.0

standard	BCR-1 recomm.	n	mean meaas.	std.dev
SiO ₂	54.36	4	55.38	0.37
TiO ₂	2.24	4	2.35	0.18
Al ₂ O ₃	13.56	5	13.50	0.27
Fe ₂ O ₃	13.40	5	13.00	0.28
MnO	0.19	5	0.18	0.01
MgO	3.46	5	3.57	0.06
CaO	6.94	4	6.63	0.07
Na ₂ O	3.26	5	3.23	0.05
K ₂ O	1.67	4	1.73	0.05

Recommended values are: Abbey (1968); \$ Flanagan (1976).

Table A.8 Duplicates determined with isotope dilution at
Max Planck Institut für Chemie, Mainz

sample spike	315		316	
	REE	REE	alkali REE	Rb-Sr Sm-Nd
Rb			2.17	2.17
Sr			98.00	98.00
La	1.12	1.16		
Ce	3.01	3.12		
Nd	2.86	2.98	4.03	4.02
Sm	1.15	1.19	1.52	1.51
Eu	0.462	0.479		

sample spike	345		346	
	alkali REE	Rb-Sr REE	alkali REE	Rb-Sr Sm-Nd
Rb	5.36	5.56	5.08	5.12
Sr	68.00	70.00	96.00	95.00
La	0.88	0.86		
Ce	2.39	2.40		
Nd	2.43	2.45	4.58	4.60
Sm	1.03	1.03	1.75	1.75
Eu	0.419	0.419		

sample spike	350		353	
	alkali REE	Rb-Sr Sm-Nd	alkali	Rb-Sr
Rb	4.06	4.10	6.87	6.69
Sr	93.00	93.00	97.00	98.00
La				
Ce				
Nd	4.29	4.30		
Sm	1.62	1.63		
Eu				

Table A.9 Standards determined with isotope dilution at
Max-Planck Institut für Chemie

spike	JB-1			AGV-1		
	alkali REE	Sm-Nd	recomm.	alkali REE	Sm-Nd	recomm.
K				24100		23900
Rb	39.00		41.20	61.00		67.00
Sr	442		435	656		657
Ba	504		490	1209		1208
La	37.85		36.00			35.00
Ce	66.85		67.00			63.00
Nd	26.45	26.60	27.00		31.95	39.00
Sm	5.08	5.11	5.16		5.78	5.90
Eu	1.48		1.50			1.70
Gd	4.76		4.80			1.00
Dy	4.22		4.10			3.50
Er	2.27		2.30			1.20
Yb	2.12		2.10			1.70
Lu	0.317		0.300			0.280

spike	BCR-1			BHVO-1		
	alkali REE	Sm-Nd	W&P recomm.	alkali REE	Sm-Nd	recomm.
K	14193		14200	4303		4370
Rb	44.30		46.80	9.25		7.96
Sr	329		332	396		326
Ba	670		676	131		132
La	25.49		24.90	15.55		17.50
Ce	53.26		53.40	38.20		33.40
Nd	28.82	28.86	28.80	24.75	24.86	22.70
Sm	6.61	6.59	6.59	6.16	6.13	5.30
Eu	1.98		1.96	2.08		1.66
Gd	6.72		6.64	6.24		5.61
Dy	6.40		6.42	5.35		4.71
Er	3.67		3.67	2.56		1.83
Yb	3.36		3.37	2.00		1.57
Lu	0.488		0.497	0.275		

spike	GSP-1			blank(pg)	
	alkali REE	Sm-Nd	recomm.	alkali REE	
K	45651		45905		
Rb	250.00		254.00	0.30	
Sr	234		233	0.03	
Ba	1293		1300		
La			191	1.40	
Ce	467		394	0.80	
Nd	218		188	0.02	
Sm	27.78	25.68	27.10	0.03	
Eu	2.34		2.40	0.03	
Gd			15.00	0.13	
Dy			5.40	0.26	
Er			3.00	0.04	
Yb			1.80	0.05	
Lu			0.230	2.04	

W&P: White & Patchett (1984)

recomm.: Flanagan (1976), Gowindaraju (1984)

Table A.10 Isotopic compositions of standards determined at
Max Planck Institut fur Chemie, Mainz

	87Sr/86Sr	143Nd/144Nd	150Nd/144Nd
BCR-1	.705010+30	.512653+16	.236438+25
BHVO-1	.703480+30	.512981+19	.236374+20
JB-1	.704120+30	.512759+16	.236478+20
AGV-1	.704000+30	.512795+13	.236477+33
GSP-1	.768780+30	.511367+13	.236487+15
La Jolla (n=7)		.511869+19	
E&A (n=6)	.707986+15		

	206Pb/204Pb	207Pb/204Pb	208Pb/204Pb	blank (pg)
NBS 982	36.626	17.086	36.534	523

Isotope data are reported relative to standards
E&A ⁸⁷Sr/⁸⁶Sr:0.70800, ¹⁴³Nd/¹⁴⁴Nd:0.511850.

Fractionation corrections were made to ⁸⁶Sr/⁸⁸Sr:0.1194 and
¹⁴⁶Nd/¹⁴⁴Nd:0.7219.

For Sr age correction 1.42*10⁻¹¹y⁻¹ and T=80Ma were used.
For Nd age correction 6,54*10⁻¹²y⁻¹ was used.

ε_{Nd} was calculated as
$$\left[\frac{^{143}\text{Nd}/^{144}\text{Nd}_\text{T}}{^{143}\text{Nd}/^{144}\text{Nd}_\text{CHUR(T)}} - 1 \right] * 10^4.$$

¹⁴³Nd/¹⁴⁴Nd_{CHUR(today)}=0.512638
¹⁴⁷Sm/¹⁴⁴Nd_{CHUR(today)}=0.1967

Errors are 2 sigma errors of the mean based on in-run statistics for Sr
and Nd.

Table A.11.1 Compositions of olivines

sample	331.1	331.2	341.1	341.2	341.3	371.1
SiO ₂	39.67	39.39	39.49	39.60	39.66	39.86
Al ₂ O ₃	0.17	0.15	0.19	0.14	0.24	0.02
FeO	14.38	14.59	15.00	15.09	14.66	15.09
MnO	0.13	0.15	0.21	0.26	0.16	0.26
MgO	45.43	45.26	44.79	44.55	45.05	44.25
CaO	0.22	0.18	0.18	0.15	0.23	0.27
Total	100.00	99.72	99.86	99.79	100.00	99.79
Mg#	84.70	84.50	84.00	83.90	84.30	83.90

sample	371.2	371.3	371.4	371.5	518I.1	KA.1
SiO ₂	39.59	39.75	39.46	39.78	39.57	39.88
Al ₂ O ₃	0.02	0.02		0.02	0.06	0.02
FeO	14.44	14.46	14.79	14.40	13.68	12.56
MnO	0.21	0.22	0.21	0.20	0.21	0.19
MgO	45.39	45.23	45.16	45.16	46.21	47.00
CaO	0.18	0.16	0.18	0.17	0.16	0.20
Total	99.83	99.84	99.81	99.73	99.89	99.85
Mg#	84.80	84.50	84.60	84.30	86.00	87.00

sample	KA.2	KA.5	KA.6	KA.7	KA.8	LIM.1
SiO ₂	40.20	40.16	40.68	40.33	40.50	40.47
Al ₂ O ₃			0.04			
FeO	11.25	12.36	11.28	10.28	10.66	11.45
MnO	0.19	0.13	0.14	0.14	0.13	0.14
MgO	47.67	46.98	47.43	48.81	48.28	47.62
CaO	0.17	0.20	0.16	0.12	0.13	0.11
Total	99.78	99.85	99.73	99.68	99.70	99.79
Mg#	87.90	86.90	87.20	89.50	88.60	87.70

sample	LIM.2	LIM.3
SiO ₂	40.27	40.35
Al ₂ O ₃	0.02	0.06
FeO	11.55	11.80
MnO	0.17	0.11
MgO	47.55	47.47
CaO	0.18	0.13
Total	99.74	99.92
Mg#	87.70	87.40

Table A.11.2 Compositions of orthopyroxenes

sample	498.1	LIM.1	LIM.2	LIM.3	LIM.4	LIM.5
SiO ₂	52.53	55.64	56.68	56.34	56.13	56.30
TiO ₂	0.21	0.02	0.03	0.01	0.04	0.05
Al ₂ O ₃	1.34	1.57	0.98	0.70	1.02	1.29
FeO	19.94	7.79	7.63	8.40	7.77	7.93
MnO		0.23	0.13	0.30	0.20	0.40
MgO	24.08	31.13	32.36	32.06	32.21	31.46
CaO	1.78	2.76	1.75	2.00	2.08	2.05
Na ₂ O	0.03	0.06			0.09	0.02
Total	99.92	99.21	99.57	99.81	99.54	99.50
Mg#	68.30	87.70	88.40	87.20	88.10	87.60

sample	LIM.6	LIM.7	LIM.8	LIM.9
SiO ₂	56.09	56.40	54.83	55.95
TiO ₂	0.03	0.04	0.11	0.06
Al ₂ O ₃	0.82	0.76	1.31	1.38
FeO	8.41	7.56	11.75	7.93
MnO	0.20	0.13	0.34	0.20
MgO	32.28	32.74	29.67	32.03
CaO	1.91	1.95	1.85	1.94
Na ₂ O	0.02		0.02	0.00
Total	99.76	99.59	99.89	99.49
Mg#	87.30	88.60	84.30	87.90

Table A.11.3 Compositions of clinopyroxenes

sample	315.1	315.2	315.3	315.4	315.5	315.6
SiO ₂	51.46	50.62	53.95	53.66	53.47	53.42
TiO ₂	0.46	0.52	0.14		0.18	
Al ₂ O ₃	5.37	5.95	1.60	2.12	2.09	1.88
FeO	9.44	8.26	5.55	6.29	5.38	5.23
MnO	0.27	0.15				
MgO	20.48	17.49	18.80	19.29	18.41	18.60
CaO	12.39	17.01	19.63	18.27	19.97	20.96
Na ₂ O						
Total	99.87	100.00	99.67	99.63	99.50	99.55
Mg#	79.40	79.00	85.80	84.50	85.90	86.10

sample	315.7	316.1	316.2	316.3	331.1	331.2
SiO ₂	53.89	54.48	53.94	53.60	56.34	56.38
TiO ₂			0.17	0.27		
Al ₂ O ₃	1.64	2.11	1.77	2.14	0.70	0.80
FeO	5.45	4.09	4.56	4.66	9.36	9.28
MnO					0.23	0.15
MgO	18.54	18.45	19.40	19.36	29.60	29.85
CaO	20.07	20.25	19.41	19.29	3.56	3.40
Na ₂ O						
Total	99.59	99.38	99.25	99.32	99.79	99.86
Mg#	85.90	88.90	88.30	88.10	84.90	85.10

sample	331.3	331.4	341.1	341.2	341.3	345.1
SiO ₂	53.76	50.24	56.39	55.14	56.41	53.57
TiO ₂	0.19	0.25		0.26		
Al ₂ O ₃	2.71	15.33	0.83	2.67	0.60	2.36
FeO	7.19	8.63	8.81	5.85	9.12	5.34
MnO	0.16		0.23		0.19	
MgO	20.53	7.94	29.69	18.30	29.85	18.47
CaO	14.99	15.94	3.49	17.05	3.62	19.70
Na ₂ O		0.89				
Total	99.53	99.91	99.44	99.27	99.79	99.44
Mg#	83.60	62.10	85.70	84.80	85.40	86.10

sample	345.2	345.3	346.1	346.2	350.1	350.2
SiO2	52.64	53.11	50.01	50.92	50.82	50.50
TiO2	0.12	0.12	0.83	0.62	0.46	0.78
Al2O3	3.52	2.86	5.18	4.85	5.37	5.93
FeO	6.56	5.21	13.07	12.37	6.57	6.62
MnO		0.17	0.30	0.17		
MgO	19.04	18.17	17.43	17.45	16.54	16.15
CaO	17.90	19.07	13.18	13.62	19.90	19.82
Na2O						
Total	99.78	98.71	100.00	100.00	99.66	99.80
Mg#	83.80	86.10	70.40	71.50	81.80	81.40

sample	350.3	350.4	353.1	368.1	371.1	371.2
SiO2	53.14	52.44	50.74	51.68	52.75	53.34
TiO2	0.13	0.18	0.68	0.39	0.22	0.21
Al2O3	2.56	3.39	2.45	3.37	2.82	2.58
FeO	4.86	5.54	19.26	9.77	6.06	6.48
MnO			0.64		0.16	0.20
MgO	17.99	17.08	16.04	16.76	19.22	19.76
CaO	20.50	21.32	10.16	17.87	18.06	16.62
Na2O					0.21	
Total	99.18	99.95	99.97	99.84	99.50	99.19
Mg#	86.80	84.50	59.70	75.40	85.00	84.60

sample	406.1	406.2	412.1	412.2	412.3	412.4
SiO2	52.81	52.56	52.36	53.81	53.50	53.48
TiO2	0.38	0.26	0.17	0.10	0.13	0.09
Al2O3	3.34	3.09	3.35	1.40	2.04	2.06
FeO	8.00	5.65	6.23	4.62	5.26	4.69
MnO	0.22	0.20	0.17	0.12	0.14	0.15
MgO	21.54	17.66	17.85	19.01	19.02	18.27
CaO	13.19	19.93	18.82	20.28	18.97	20.43
Na2O	0.20	0.22	0.20	0.07	0.18	0.14
Total	99.68	99.57	99.15	99.41	99.25	99.31
Mg#	82.80	84.80	83.60	88.10	88.50	87.40

sample	412.5	412.6	412.7	412.8	435.1	435.2
SiO2	50.35	53.55	50.97	53.65	53.66	53.49
TiO2	0.43	0.11	0.49	0.10	0.22	0.18
Al2O3	6.06	1.63	4.65	0.10	2.35	1.80
FeO	6.94	4.63	6.87	6.76	4.97	5.36
MnO	0.09	0.16	0.16	0.16	0.06	0.15
MgO	17.09	18.51	17.63	18.54	18.13	18.52
CaO	18.76	20.66	18.95	20.40	20.33	20.30
Na2O	0.15	0.15	0.13	0.14	0.15	0.10
Total	99.87	99.40	99.86	99.85	99.87	99.90
Mg#	81.40	87.70	82.10	88.20	86.70	86.00

sample	435.3	435.4	500.1	500.2	500.3	518I.1
SiO2	54.17	53.42	50.80	52.07	52.52	52.83
TiO2	0.14	0.30	0.66	0.38	0.31	0.27
Al2O3	1.49	1.79	3.45	2.23	2.22	2.77
FeO	4.75	5.31	14.36	17.64	10.08	5.72
MnO	0.12	0.05	0.24	0.31	0.25	0.16
MgO	18.76	18.66	17.20	21.75	16.78	19.19
CaO	20.33	20.20	12.85	5.57	17.64	18.14
Na2O	0.16	0.13	0.24	0.02	0.19	0.20
Total	99.93	99.86	99.70	99.97	100.00	99.29
Mg#	87.70	86.30	68.30	68.80	74.80	85.60

sample	518I.2	518I.3	518I.4	518I.5	534.1	544.1
SiO2	52.35	52.59	52.02	53.82	49.82	52.03
TiO2	0.46	0.25	0.41	0.17	0.79	0.47
Al2O3	3.85	3.00	3.61	2.31	5.15	3.92
FeO	7.15	6.20	6.98	6.87	12.47	4.89
MnO	0.20	0.14	0.14	0.19	0.27	0.27
MgO	20.44	19.22	18.03	22.04	15.86	17.14
CaO	15.18	17.84	18.11	13.87	15.44	20.53
Na2O	0.10	0.20	0.25	0.12	0.19	0.27
Total	99.73	99.45	99.55	99.39	100.00	99.53
Mg#	83.60	84.70	82.20	85.20	69.40	86.20

Table A.11.4 Compositions of plagioclases

sample	315.1	315.2	315.3	315.4	316.2	345.1
SiO ₂	47.12	46.64	46.22	46.85	48.36	50.07
Al ₂ O ₃	33.51	33.77	34.19	33.52	32.59	29.96
FeO	0.58	0.59	0.55	0.58	0.34	0.78
MgO	0.31	0.26	0.26	0.20	0.33	0.32
CaO	17.36	17.30	17.84	17.48	16.69	13.82
Na ₂ O	1.12	1.34	0.94	1.37	1.69	4.97
K ₂ O		0.10				0.08
Total	100.00	100.00	100.00	100.00	100.00	100.00
An	89.60	87.50	91.30	86.50	84.50	70.60

sample	350.1	368.1	370.1	370.2	370.3	498.1
SiO ₂	50.86	51.73	48.84	47.19	46.64	48.18
Al ₂ O ₃	30.91	30.15	32.08	33.06	33.81	32.01
FeO	0.65	0.94	0.87	0.81	0.82	0.84
MgO	0.41	0.27	0.21	0.15	0.12	0.13
CaO	14.49	13.90	15.91	16.93	17.46	16.72
Na ₂ O	2.68	3.01	2.09	1.79	1.15	2.12
K ₂ O				0.07		
Total	100.00	100.00	100.00	100.00	100.00	100.00
An	74.90	71.90	80.80	83.80	89.40	82.80

sample	498.2	500.1	500.2	500.3	516.2	516.3
SiO ₂	46.80	45.91	47.39	46.84	50.09	48.17
Al ₂ O ₃	32.82	33.84	33.16	33.70	30.75	32.57
FeO	0.89	0.58	0.65	0.71	0.74	0.57
MgO	0.02					
CaO	17.89	18.36	17.38	17.58	14.85	16.72
Na ₂ O	1.55	1.30	1.38	1.16	1.10	1.89
K ₂ O	0.02	0.01	0.04	0.01	2.47	0.08
Total	100.00	100.00	100.00	100.00	100.00	100.00
An	86.50	88.80	87.40	89.30	72.20	82.80

sample	516.4	516.5	516.6	516.7	518E.1	518E.2
SiO ₂	48.89	48.81	51.93	51.63	47.44	48.01
Al ₂ O ₃	32.45	31.93	29.78	30.12	32.91	32.17
FeO	0.70	0.61	0.64	0.44	0.80	0.66
MgO						
CaO	15.63	16.04	13.60	14.23	17.05	16.85
Na ₂ O	2.27	2.25	4.03	3.55	1.76	2.30
K ₂ O	0.06	0.36	0.02	0.03	0.04	0.01
Total	100.00	100.00	100.00	100.00	100.00	100.00
An	79.10	78.30	65.10	69.00	84.30	80.20

sample	518E.3	518E.4	518E.5	544.1	544.2	544.3
SiO2	50.96	51.76	50.88	49.63	49.68	49.21
Al2O3	30.88	30.68	30.79	31.33	30.80	31.11
FeO	0.52	0.52	0.60	0.50	0.46	0.45
MgO				0.27	0.26	0.28
CaO	14.44	13.49	14.80	15.66	16.16	16.34
Na2O	3.18	3.53	2.91	2.57	2.59	2.57
K2O	0.02	0.02	0.02		0.02	0.02
Total	100.00	100.00	100.00	100.00	100.00	100.00
An	71.40	67.80	73.80	77.10	77.50	77.90

sample	544.4	544.5	544.6
SiO2	49.30	49.08	49.43
Al2O3	32.41	31.99	32.12
FeO	0.37	0.40	0.37
MgO			
CaO	15.47	16.12	16.01
Na2O	2.41	2.41	2.06
K2O	0.04		0.01
Total	100.00	100.00	100.00
An	78.00	78.80	81.10

Table A.12 Major and trace element compositions of whole rocks and glasses

sample	30	33	35	36	38	39
unit	A	A	A	A	A	A
rock type	pillow	pillow	pillow	pillow	pillow	pillow
SiO ₂	43.13	33.91	54.59	54.88	49.65	49.54
TiO ₂	0.50	0.41	0.61	0.65	0.68	0.69
Al ₂ O ₃	13.89	10.92	19.18	19.26	15.65	16.67
FeO	8.85	9.34	9.84	9.81	8.01	7.67
MnO	0.17	0.11	0.06	0.04	0.09	0.08
MgO	9.06	5.69	5.98	5.86	8.64	8.90
CaO	21.54	36.57	0.70	0.43	11.32	11.28
Na ₂ O	0.60	0.81	0.40	0.33	0.55	0.75
K ₂ O	2.46	2.13	8.59	8.72	5.32	4.33
P ₂ O ₅	0.07	0.12	0.06	0.02	0.10	0.09
H ₂ O	4.31	2.95	9.55	6.67	5.22	5.09
CO ₂	11.31	18.73	0.32	0.21	6.10	5.04
Fe ₂ O ₃ /FeO	2.65	5.69	11.66	54.16	5.76	2.99
K	20400	17700	71300	72400	44200	35900
Rb	35	16	85	90	49	45
Sr	106	132	134	156	105	106
Ba	10	34	102	109	54	61
Zr	22+	17+	27+	29+	40+	33+
Nb						
Y	11	10	6	3	15	16
Ti	3000	2460	3660	3900	4080	4140
V						
Cr	560	1060	286	385	205	192
Mn	1320	852	465	310	697	620
Co	25	26	37	43	25	28
Ni	177	195	59	63	58	57
depth	15	20	40	40	90	90

sample	42	43	45	46	47	49
unit	A	A	A	A	A	A
rock type	tube	tube	sill	sill	large body	pillow
SiO ₂	54.71	53.20	52.76	48.21	54.76	54.68
TiO ₂	0.71	0.68	0.27	0.30	0.70	0.77
Al ₂ O ₃	16.11	16.95	8.06	9.10	15.34	17.18
FeO	7.98	7.32	9.00	8.70	8.76	8.03
MnO	0.08	0.15	0.17	0.16	0.14	0.06
MgO	8.02	7.26	22.44	27.25	8.47	8.33
CaO	10.13	12.12	6.23	5.56	7.88	8.70
Na ₂ O	1.99	2.00	0.88	0.64	1.75	1.86
K ₂ O	0.19	0.16	0.17	0.05	2.15	0.34
P ₂ O ₅	0.07	0.06	0.03	0.03	0.06	0.03
H ₂ O	2.00	1.91	5.60	5.73	3.40	3.61
CO ₂	0.09	1.99	0.74	0.15	0.89	0.30
Fe ₂ O ₃ /FeO	1.83	2.57	0.61	0.48	1.89	4.72
K	1580	1330	1410	415	17800	2820
Rb	15	15	6	13	79	9
Sr	96	102	59	34	69	104
Ba	20	34	59	10	51	22
Zr	38+	34+	16+	15+	32+	37+
Nb						
Y	17	17	6	6	17	9
Ti	4260	4080	1620	1800	4200	4620
V						
Cr	212	197	2120	1970	137	197
Mn	620	1160	1320	1240	1080	465
Co	33	21	86	72	35	37
Ni	39	38	1240	784	37	36
depth	95	95	87	85	128	128

+ recalculated Zr concentrations (see chapter 4)

sample unit	50 A	60 A	61 A	62 A	63 A	65* A
rock type	pillow	pillow	pillow	pillow	pillow	pill.gl.
SiO2	52.96	51.85	56.30	57.11	51.73	55.10
TiO2	0.76	0.71	0.80	0.85	0.76	0.55
Al2O3	17.07	16.36	19.06	19.18	17.62	15.70
FeO	8.34	8.64	6.31	6.12	8.22	7.73
MnO	0.05	0.16	0.06	0.04	0.07	0.16
MgO	9.04	8.42	4.90	4.94	8.46	7.31
CaO	9.75	12.02	9.95	9.05	11.16	11.30
Na2O	1.79	1.68	2.34	2.32	1.82	1.92
K2O	0.15	0.10	0.22	0.31	0.06	0.16
P2O5	0.08	0.10	0.07	0.08	0.07	0.07
H2O	2.87	1.53	2.04	1.96	2.59	1.90
CO2	0.26	0.14	0.19	0.09	0.09	
Fe2O3/FeO	3.05	0.68	3.67	5.70	2.60	
K	1250	830	1830	2570	498	1330
Rb	10	12	13	17	12	
Sr	100	93	112	115	100	
Ba	10	22	31	49	43	
Zr	36+	34+	40+	44+	38+	
Nb						
Y	24	19	17	14	19	
Ti	4560	4260	4800	5100	4560	3300
V						
Cr	203	215	208	186	225	
Mn	387	1240	465	310	542	1240
Co	36	36	45	11	33	
Ni	39	37	49	24	44	
depth	128	115	115	120	120	140

sample unit	67 A	68 A	69 A	70 A	306* A	420 A
rock type	tube	tube	pillow	sill	pill.gl.	pillow
SiO2	52.08	53.93	59.36	53.13	55.15	44.12
TiO2	0.70	0.75	0.72	0.36	0.66	0.59
Al2O3	15.90	16.51	16.11	10.67	15.34	14.42
FeO	6.98	8.20	6.53	9.06	8.58	7.04
MnO	0.22	0.09	0.15	0.21	0.18	0.12
MgO	6.16	8.01	5.00	18.32	6.54	8.08
CaO	15.80	10.34	9.73	7.45	10.73	21.00
Na2O	2.00	1.97	2.16	0.68	2.43	0.84
K2O	0.10	1.97	0.17	0.09	0.16	3.68
P2O5	0.06	0.06	0.08	0.03		0.10
H2O	1.76	2.27	2.11	5.34	5.10	16.54
CO2	3.46	0.23	0.63	0.76		
Fe2O3/FeO	2.20	1.77	6.28	0.82		
K	830	16400	1410	747	1330	30500
Rb	15	5	13	15		25
Sr	94	100	96	78		99
Ba	13	41	24	10		56
Zr	34+	35+	35+	17+		24
Nb						0.8
Y	20	16	16	7		16
Ti	4200	4500	4320	2160	3960	3540
V						157
Cr	183	202	169	1740		99
Mn	1700	697	1160	1630	1390	929
Co	22	32	19	68		
Ni	29	38	31	914		
depth	140	140	140	140	130	10

sample	421	422	423	424	425	426
unit	A	A	A	A	A	A
rock type	pillow	pillow	pillow	pillow	pillow	pillow
SiO2	50.48	53.62	54.84	52.32	44.97	53.47
TiO2	0.63	0.72	0.76	0.64	0.45	0.52
Al2O3	16.53	16.94	17.65	15.99	12.40	17.15
FeO	8.06	8.33	8.08	7.67	7.90	9.01
MnO	0.09	0.08	0.08	0.10	0.11	0.09
MgO	11.01	9.97	7.67	11.75	10.32	8.19
CaO	7.62	3.54	3.69	6.58	20.26	3.63
Na2O	1.38	0.52	0.45	0.90	0.88	0.36
K2O	3.98	6.25	6.76	4.05	2.68	7.54
P2O5	0.22	0.03	0.02		0.02	0.05
H2O	9.75	10.35	9.13	9.16	14.90	10.16
CO2						
Fe2O3/FeO						
K	33000	51900	56100	33600	22200	62600
Rb	24	36	43	31	20	2
Sr	75	91	123	134	107	41
Ba	25	66	47	43	76	70
Zr	33	34	35	33	20	41
Nb	0.4	0.9	0.3	0.3	0.3	0.3
Y	17	20	18	19	13	11
Ti	3780	4320	4560	3840	2700	3120
V	217	181	166	226	183	173
Cr	113	156	146	222	447	252
Mn	697	620	620	774	852	697
Co						
Ni						
depth	20	30	40	50	70	80

sample	427	537
unit	A	A
rock type	pillow	pillow
SiO2	51.06	47.87
TiO2	0.62	0.73
Al2O3	15.14	16.76
FeO	8.54	6.20
MnO	0.10	0.10
MgO	11.03	11.05
CaO	8.86	12.67
Na2O	0.69	1.49
K2O	3.95	2.35
P2O5	0.01	0.08
H2O	9.84	11.96
CO2		
Fe2O3/FeO		
K	32800	19500
Rb	31	14
Sr	113	73
Ba	48	
Zr	28	27
Nb	1.6	1.1
Y	19	19
Ti	3720	4380
V	228	
Cr	355	
Mn	774	774
Co		
Ni		
depth	90	130

sample unit	51 B	53 B	58 B	71 B	74 B	84 B
rock type	pillow	pillow	pillow	pillow	pillow	pillow
SiO2	51.79	51.70	51.16	51.44	50.71	51.15
TiO2	0.62	0.64	0.69	0.63	0.63	0.62
Al2O3	15.43	15.85	16.77	16.01	15.35	15.69
FeO	8.13	8.01	7.83	8.29	7.23	7.93
MnO	0.16	0.16	0.15	0.14	0.14	0.18
MgO	11.18	11.73	9.73	11.89	11.12	8.72
CaO	5.76	6.06	9.23	6.02	9.22	13.60
Na2O	5.23	4.50	3.53	3.46	4.91	1.67
K2O	1.65	1.31	3.53	3.46	0.64	0.38
P2O5	0.05	0.04	0.07	0.06	0.05	0.06
H2O	5.75	4.84	4.69	6.09	5.53	2.20
CO2	0.83	0.59	0.17	0.58	2.46	2.50
Fe2O3/FeO	2.33	2.06	2.06	2.09	2.08	2.35
K	13700	10900	29300	28700	5310	3150
Rb	27	14	19	31	17	19
Sr	31	75	162	93	64	93
Ba	25	54	15	10	10	10
Zr	19+	31+	31+	28+	30+	29+
Nb						
Y	14	16	17	16	13	16
Ti	3720	3840	4140	3780	3780	3720
V						
Cr	369	357	371	408	471	404
Mn	1240	1240	1160	1080	1080	1390
Co	34	42	35	38	28	26
Ni	106	125	91	114	140	157
depth	190	190	250	170	210	265

sample unit	85 B	87* B	88 B	89 B	323* B	324.1* B
rock type	pillow	pill.gl.	pillow	pillow	pill.gl.	pill.gl.
SiO2	52.55	52.35	52.23	50.72	53.83	55.69
TiO2	0.65	0.64	0.67	0.65	0.63	0.80
Al2O3	16.21	16.15	16.64	16.14	15.58	14.96
FeO	8.68	7.48	7.92	8.26	7.84	9.77
MnO	0.12	0.07	0.12	0.14	0.15	0.19
MgO	8.85	7.86	8.50	9.84	7.54	5.93
CaO	10.52	12.34	11.43	12.33	12.17	10.22
Na2O	2.02	1.96	1.94	1.70	2.15	2.26
K2O	0.34	0.09	0.47	0.16	0.09	0.16
P2O5	0.07	0.06	0.47	0.05		
H2O	2.68	1.98	2.47	2.16	3.88	4.69
CO2	0.21		0.20	0.69		
Fe2O3/FeO	2.91		1.68	1.84		
K	2820	747	3900	1330	747	1330
Rb	20		12	4		
Sr	100		103	91		
Ba	10		56	56		
Zr	31+		30+	30+		
Nb						
Y	17		17	19		
Ti	3900	3840	4020	3900	3780	4800
V						
Cr	421		364	350		
Mn	939	542	929	1080	1160	1470
Co	38		43	41		
Ni	136		100	100		
depth	265	260	260	260	260	265

sample	324.2*	325*	326.2*	341.1*	341.2*	455
unit	B	B	B	B	B	B
rock type	pill.gl.	pill.gl.	pill.gl.	pill.gl.	pill.gl.	pillow
SiO2	53.77	53.58	55.81	53.53	56.93	51.97
TiO2	0.62	0.58	0.78	0.57	0.50	0.63
Al2O3	15.40	15.49	15.05	15.17	14.88	15.60
FeO	7.53	7.53	9.83	7.79	7.52	7.72
MnO	0.14	0.15	0.19	0.14	0.16	0.10
MgO	8.14	7.99	5.99	8.16	6.91	13.07
CaO	12.38	12.44	10.09	12.72	10.66	5.28
Na2O	1.94	2.15	2.09	1.84	2.21	3.28
K2O	0.08	0.09	0.17	0.09	0.22	2.31
P2O5						0.04
H2O	4.35	4.43	5.46	4.69	4.26	10.76
CO2						
Fe2O3/FeO						
K	664	747	1410	747	1820	19200
Rb						
Sr						
Ba						
Zr						
Nb						
Y						
Ti	3720	3480	4680	3420	3000	3780
V						
Cr						
Mn	1080	1160	1470	1080	1240	774
Co						
Ni						
depth	265	260	265	190	190	190

sample unit	78 C	79 C	80 C	81 C	82 C	90 C
rock type	dike	dike	dike	s.flow	s.flow	s.flow
SiO ₂	54.70	55.92	57.88	56.47	57.39	61.99
TiO ₂	0.47	0.49	0.48	1.34	1.30	1.13
Al ₂ O ₃	15.60	14.65	15.33	15.92	15.85	14.09
FeO	7.69	8.73	7.71	10.83	10.50	9.50
MnO	0.12	0.13	0.09	0.22	0.02	0.19
MgO	8.15	8.16	6.85	3.34	2.72	2.73
CaO	11.62	10.06	9.80	8.06	7.88	6.64
Na ₂ O	1.56	1.61	1.66	2.76	2.83	2.49
K ₂ O	0.05	0.22	0.15	0.97	1.21	1.15
P ₂ O ₅	0.04	0.04	0.04	0.10	0.11	0.09
H ₂ O	2.06	2.14	5.62	1.90	1.42	1.55
CO ₂	0.69	0.18	0.46	0.56	0.14	0.16
Fe ₂ O ₃ /FeO	1.76	0.96	2.43	2.31	1.91	1.90
K	415	1830	1250	8050	10000	9550
Rb	11	17	17	35	41	27
Sr	72	71	70	91	62	77
Ba	16	13	10	69	76	10
Zr	22+	23+	22+	47+	46+	41+
Nb						
Y	13	12	9	31	37	30
Ti	2820	2940	2880	8030	7790	6770
V						
Cr	265	231	240	38	39	35
Mn	929	1010	697	1700	1470	1470
Co	32	38	30	43	36	5
Ni	56	53	54	15	18	11
depth	280	280	280	275	275	279

sample unit	91 C	93 C	94 C	96 C	97 C	98 C
rock type	s.flow	s.flow	s.flow	dike	s.flow	sill
SiO ₂	58.80	58.31	61.78	52.80	62.30	60.12
TiO ₂	1.22	1.31	1.18	1.38	1.17	0.92
Al ₂ O ₃	15.38	15.98	13.78	16.35	14.22	14.92
FeO	10.14	9.74	9.95	12.20	9.08	8.77
MnO	0.23	0.21	0.18	0.16	0.20	0.13
MgO	3.80	2.95	3.07	6.74	2.98	4.24
CaO	7.71	7.86	6.37	6.88	6.44	8.07
Na ₂ O	2.48	2.69	2.45	2.91	2.75	2.33
K ₂ O	0.17	0.86	1.12	0.48	0.75	0.43
P ₂ O ₅	0.08	0.10	0.11	0.10	0.10	0.07
H ₂ O	1.62	1.53	1.70	3.83	1.55	1.49
CO ₂	0.16	0.11	0.16	0.95	0.27	0.14
Fe ₂ O ₃ /FeO	1.76	1.86	2.23	3.13	2.16	1.81
K	1410	7140	9300	3980	6230	3570
Rb	6	36	40	9	29	18
Sr	82	90	78	97	80	82
Ba	15	51	50	67	56	47
Zr	45+	45+	46+	51+	48+	38+
Nb						
Y	26	27	30	30	30	23
Ti	7310	7850	7070	8270	7010	5520
V						
Cr	36	40	38	49	30	72
Mn	1780	1630	1390	1240	1550	1010
Co	26	38	33	50	26	33
Ni	13	10	11	22	9	22
depth	278	273	289	275	284	282

sample unit	99/ C	100 C	103 C	104 C	105 C	310/ C
rock type	sill gl.	dike	dike	dike	sill	dike gl.
SiO ₂	56.16	55.18	52.21	57.87	52.43	58.09
TiO ₂	0.45	0.53	0.67	0.67	0.39	1.26
Al ₂ O ₃	16.21	16.57	16.54	15.24	11.25	13.73
FeO	7.31	7.82	9.00	8.24	9.21	13.75
MnO	0.12	0.12	0.15	0.10	0.23	0.23
MgO	6.66	6.85	8.41	6.61	17.12	3.57
CaO	10.80	10.53	11.10	9.03	8.25	8.13
Na ₂ O	2.04	2.15	1.80	2.10	1.03	1.86
K ₂ O	0.21	0.18	0.06	0.08	0.04	0.67
P ₂ O ₅	0.03	0.05	0.06	0.06	0.04	
H ₂ O	2.30	2.31	2.74	2.00	4.59	8.03
CO ₂		0.52	1.22	0.15	0.55	
Fe ₂ O ₃ /FeO		2.10	1.85	1.94	3.67	
K	1740	1490	498	664	332	5560
Rb		5	4	13	14	
Sr		88	95	88	81	
Ba		16	18	18	10	
Zr		27+	32+	33+	18+	
Nb						
Y		16	20	16	7	
Ti	2700	3180	4020	4020	2340	7550
V						
Cr		150	176	142	1250	
Mn	929	929	1160	774	1780	1780
Co		35	37	290	66	
Ni		44	42	34	686	
depth	282	282	282	282	292	275

sample unit	310* C	311/ C	312/ C	314/ C	317* C	318* C
rock type	s.flow gl.	dike gl.	dike gl.	dike gl.	s.flow gl.	s.flow gl.
SiO ₂	55.57	55.44	56.42	56.27	55.32	59.07
TiO ₂	0.62	0.68	0.45	0.43	0.83	1.37
Al ₂ O ₃	15.33	16.17	15.23	15.30	15.75	13.59
FeO	8.35	7.41	7.73	7.88	9.36	11.90
MnO	0.13	0.16	0.12	0.16	0.17	0.21
MgO	6.39	6.42	6.77	6.70	5.85	3.04
CaO	10.91	11.05	10.92	11.17	10.24	7.72
Na ₂ O	2.21	2.14	2.13	1.90	2.20	2.81
K ₂ O	0.21	0.31	0.25	0.19	0.18	0.29
P ₂ O ₅		0.23			0.08	
H ₂ O	5.56	2.32	6.16	5.29	1.40	6.55
CO ₂						
Fe ₂ O ₃ /FeO						
K	1740	2570	2080	1580	1490	2410
Rb						
Sr						
Ba						
Zr						
Nb						
Y						
Ti	3720	4080	2700	2580	4980	8210
V						
Cr						
Mn	1010	1240	929	1240	1320	1630
Co						
Ni						
depth	275	282	282	285	275	281

sample unit	320/ C	321/ C	539 C	540 C	541 C	542 C
rock type	dike gl.	dike gl.	s.flow	s.flow	s.flow	s.flow
SiO2	56.63	55.45				61.29
TiO2	0.43	0.63				1.12
Al2O3	15.28	15.07				13.85
FeO	7.92	7.97				9.92
MnO	0.13	0.15				0.20
MgO	7.46	7.46				3.67
CaO	10.86	11.18				6.49
Na2O	1.93	1.92				2.58
K2O	0.19	0.17				0.74
P2O5						0.13
H2O	5.06	5.44				2.93
CO2						
Fe2O3/FeO						
K	1580	1410				6140
Rb			6	8	7	21
Sr			88	86	74	79
Ba						
Zr			51	47	34	42
Nb			0.5	1.3	1.6	2.1
Y			31	31	20	28
Ti	2580	3780				6710
V						
Cr						
Mn	1010	1160				1550
Co						
Ni						
depth	280	280	275	275	275	290

sample	106	107	110	114	117
unit	D	D	D	D	D
rock type	pillow	pillow	pillow	pillow	large body
SiO ₂	54.07	51.97	52.32	51.19	50.57
TiO ₂	0.70	0.73	0.72	0.77	0.80
Al ₂ O ₃	16.84	17.06	16.91	15.32	15.18
FeO	8.98	9.39	9.01	7.56	8.96
MnO	0.11	0.12	0.18	0.11	0.16
MgO	9.09	10.70	10.29	11.80	12.50
CaO	6.15	7.43	6.70	9.68	9.27
Na ₂ O	1.23	1.46	1.12	2.80	1.35
K ₂ O	2.76	1.08	2.65	1.70	1.15
P ₂ O ₅	0.06	0.06	0.10		0.06
H ₂ O	5.10	5.50	5.03	3.62	4.91
CO ₂	0.24	0.26	1.03	1.39	0.10
Fe ₂ O ₃ /FeO	3.20	3.18	2.15	2.73	2.31
K	22900	8970	22000	14100	9550
Rb	35	29	31	11	22
Sr	100	83	84	140	80
Ba	26	21	25	50	22
Zr	33+	31+	35+	36+	36+
Nb					
Y	17	14	23	20	19
Ti	4200	4380	4320	4620	4800
V					
Cr	219	250	135	401	641
Mn	852	929	1390	852	1240
Co	31	34	36	42	50
Ni	43	45	38	140	188
depth	380	375	365	400	435

sample unit	120 E	122 E	126 E	129 E	130 E	131 E
rock type	pillow	pillow	dike	s.flow	pillow	pillow
SiO2	50.63	52.19	57.31	54.26	53.12	54.14
TiO2	0.79	1.30	0.79	0.72	0.80	0.77
Al2O3	14.95	17.28	16.57	17.19	18.36	17.25
FeO	9.16	11.69	8.89	7.90	8.38	8.46
MnO	0.24	0.17	0.16	0.14	0.23	0.22
MgO	10.48	6.38	4.50	6.97	8.83	9.53
CaO	7.87	7.62	9.04	9.42	4.95	3.78
Na2O	4.03	2.96	2.44	2.73	2.82	2.65
K2O	1.78	0.32	0.23	0.60	2.43	3.13
P2O5	0.08	0.32	0.07	0.07	0.07	0.07
H2O	5.35	2.69	1.77	1.95	3.86	3.84
CO2	1.27	0.08	0.08	0.35	0.36	0.28
Fe2O3/FeO	2.13	2.33	1.79	2.68	3.38	3.27
K	14800	2660	1910	4980	20200	26000
Rb	22	17	16	12	25	25
Sr	145	100	99	114	185	1671
Ba	51	48	25	50	79	88
Zr	36+	49+	40+	38+	46+	44+
Nb						
Y	20	33	20	19	21	24
Ti	4740	7790	4740	4320	4800	4620
V						
Cr	353	37	24	54	35	34
Mn	1860	1320	1240	1080	1780	1700
Co	47	51	36	37	31	37
Ni	162	15	12	47	40	38
depth	440	490	554	565	570	570

sample unit	132 E	133 E	135 E	402* E	403 E	404 E
rock type	s.flow	s.flow	dike	s.flow gl.	sill	tube
SiO2	55.28	52.67	51.92	59.06	53.28	52.12
TiO2	0.80	0.81	0.87	1.05	0.60	0.59
Al2O3	17.10	17.75	18.12	14.92	15.61	15.18
FeO	7.83	8.36	10.35	11.82	8.70	7.23
MnO	0.10	0.14	0.10	0.18	0.10	0.13
MgO	6.87	7.81	8.01	4.25	9.67	11.17
CaO	8.06	9.23	7.80	7.72	10.03	11.63
Na2O	2.98	2.85	2.66	0.65	1.87	1.91
K2O	0.90	0.29	0.10	0.34	0.15	0.03
P2O5	0.08	0.08	0.07			0.01
H2O	2.48	2.66	3.03	9.25	6.09	4.83
CO2	0.41	0.48	0.12			
Fe2O3/FeO	3.24	3.22	4.11			
K	7470	2410	830	2820	1250	249
Rb	20	9	12		1	1
Sr	123	119	102		76	89
Ba	46	52	22		16	16
Zr	42+	42+	43+		23	31
Nb					0.3	0.5
Y	30	17	23		14	19
Ti	4860	4860	5220	6290	3600	3540
V					270	247
Cr	61	41	32		199	238
Mn	774	1080	774	1390	774	1010
Co	34	34	44			
Ni	39	39	16			
depth	572	570	570	510	510	510

sample unit	405 E	431 E	432 E	433 E	434 E	435* E
rock type	sill	s.flow	s.flow	s.flow	s.flow	s.flow gl.
SiO2	56.66	56.61	55.17	53.19	56.06	56.20
TiO2	0.47	0.91	0.88	0.91	0.84	0.68
Al2O3	14.17	17.85	16.43	17.26	16.75	16.10
FeO	7.59	7.81	8.10	8.33	6.88	7.90
MnO	0.10	0.12	0.12	0.11	0.15	0.14
MgO	10.52	5.29	7.18	9.04	6.74	6.37
CaO	7.97	7.67	8.26	8.37	9.80	10.46
Na2O	2.35	3.30	2.86	2.77	2.63	1.98
K2O	0.17	1.04	0.96	0.08	0.13	0.14
P2O5		0.03	0.03	0.01	0.01	
H2O	4.97	3.10	5.05	6.40	5.75	3.19
CO2						
Fe2O3/FeO						
K	1410	8630	7970	664	1080	1160
Rb	1	23	30		1	
Sr	94	123	116		120	
Ba	11	33	51			
Zr	29	49	46		44	
Nb	0.5	0.3	1.3		1.7	
Y	14	28	23		20	
Ti	2820	5460	5280	5460	5040	4080
V	256	309	278	304		
Cr	298	59	49	38		
Mn	774	929	929	852	1160	1080
Co						
Ni						
depth	505	551	550	549	545	549

sample unit	436 E	437 E	439 E	440 E
rock type	s.flow	s.flow	dike	s.flow
SiO2	55.56	55.81	58.25	54.06
TiO2	0.63	0.67	0.78	0.86
Al2O3	16.24	16.68	15.04	16.59
FeO	7.39	6.93	8.87	7.84
MnO	0.13	0.12	0.14	0.16
MgO	6.93	7.77	6.31	7.20
CaO	9.74	9.49	7.76	9.74
Na2O	2.53	2.42	2.58	2.84
K2O	0.82	0.10	0.17	0.69
P2O5	0.02	0.01	0.07	0.02
H2O	4.40	5.37	4.31	5.26
CO2				
Fe2O3/FeO				
K	6810	830	1410	5730
Rb	17	1	2	12
Sr	113	118	98	115
Ba		44		27
Zr	41	42	39	44
Nb	0.3	0.5	0.3	1.2
Y	18	19	39	20
Ti	3780	4020	4680	5160
V		309		268
Cr		23		56
Mn	1010	929	1080	1240
Co				
Ni				
depth	543	540	550	555

sample unit	139 F	142 F	144 F	145 F	149 F	152 F
rock type	large body	pillow	pillow	large body	sill	tube
SiO ₂	53.93	52.75	56.10	54.22	46.75	55.17
TiO ₂	0.72	0.75	0.70	0.74	0.19	0.67
Al ₂ O ₃	16.30	17.29	15.98	16.48	5.77	15.55
FeO	8.28	8.85	8.48	8.03	8.47	8.52
MnO	0.11	0.10	0.15	0.13	0.15	0.14
MgO	8.66	10.04	4.88	7.71	34.37	5.30
CaO	9.39	6.77	10.34	10.09	3.68	11.53
Na ₂ O	2.36	2.12	2.25	2.34	0.55	2.36
K ₂ O	0.17	1.23	1.06	0.19	0.06	0.70
P ₂ O ₅	0.06	0.08	0.07	0.06	0.02	0.07
H ₂ O	2.14	3.75	1.42	1.78	4.28	1.53
CO ₂	0.26	0.44	0.55	0.13	0.13	1.68
Fe ₂ O ₃ /FeO	2.47	2.89	1.95	1.63	0.29	2.17
K	1410	10200	8800	1580	498	5810
Rb	5	12	27	4	3	14
Sr	95	91	87	103	36	96
Ba	47	50		70	45	52
Zr	33+	37+	36+	34+	13+	33+
Nb						
Y	19	24	21	19	2	21
Ti	4320	4500	4200	4440	1140	4020
V						
Cr	187	158	148	161	2190	131
Mn	852	774	1160	1010	1160	1080
Co	41	40	13	35	95	29
Ni	49	75	29	44	1290	28
depth	660	670	745	750	740	735

sample unit	154 F	160 F	163* F	165 F	372 F	373 F
rock type	pillow	tube	pill.gl.	pillow	pillow	pillow
SiO ₂	52.48	53.60	54.96	52.15	52.65	53.09
TiO ₂	0.53	1.25	0.70	0.75	0.72	0.72
Al ₂ O ₃	16.82	17.46	16.36	17.23	16.69	16.82
FeO	8.94	10.56	8.13	8.72	9.09	9.08
MnO	0.13	0.12	0.14	0.11	0.14	0.14
MgO	7.28	5.90	6.36	9.68	10.24	9.93
CaO	10.44	7.96	10.86	8.69	7.35	6.43
Na ₂ O	2.27	2.97	2.22	2.15	2.43	2.30
K ₂ O	1.00	0.08	0.22	0.46	0.57	1.37
P ₂ O ₅	0.06	0.10		0.06	0.12	0.12
H ₂ O	2.48	2.33	2.51	4.61	3.60	4.07
CO ₂	0.65	0.59		0.58	0.18	0.24
Fe ₂ O ₃ /FeO	1.69	3.58		2.67	7.14	10.48
K	8300	664	1830	3820	4730	11400
Rb	21	9		7	7	10
Sr	78	112		109	99	95
Ba	10	54		62	10	10
Zr	26+	48+		37+	35+	37+
Nb						
Y	14	30		17	36	23
Ti	3180	7490	4200	4500	4320	4320
V						
Cr	234	50		164	161	164
Mn	1010	929	1080	852	1080	1080
Co	8	48		37	18	21
Ni	61	14		49	42	37
depth	735	810	810	720	745	740

sample unit	374 F	375 F	376 F	377 F	378 F	379 F
rock type	pillow	pillow	pillow	pillow	pillow	pillow
SiO ₂	53.40	53.72	52.86	53.13	51.66	51.38
TiO ₂	0.74	0.75	0.73	0.73	0.72	0.70
Al ₂ O ₃	17.17	17.48	17.14	17.36	17.00	16.63
FeO	8.72	8.19	8.73	8.72	8.76	8.94
MnO	0.12	0.11	0.12	0.13	0.13	0.15
MgO	9.23	9.07	9.48	9.39	9.71	9.64
CaO	7.26	7.86	8.23	7.95	9.46	9.30
Na ₂ O	2.36	2.13	1.91	1.64	1.86	2.26
K ₂ O	0.93	0.65	0.73	0.89	0.62	0.91
P ₂ O ₅	0.06	0.05	0.06	0.05	0.07	0.10
H ₂ O	3.44	4.01	3.86	4.23	3.46	3.87
CO ₂	0.16	0.16	0.36	0.16	1.08	2.03
Fe ₂ O ₃ /FeO	6.10	8.04	5.54	6.00	4.90	4.21
K	7720	5400	6060	7390	5150	7550
Rb	14	7	8	7	6	5
Sr	102	104	101	99	102	99
Ba	10	10	10	10	10	10
Zr	37+	38+	35+	37+	37+	35+
Nb						
Y	16	17	20	17	23	19
Ti	4440	4500	4380	4380	4320	4200
V						
Cr	150	167	167	171	173	172
Mn	929	852	929	1010	1010	1160
Co	17	6	28	24	14	19
Ni	37	40	43	40	44	45
depth	730	720	720	710	690	690

sample unit	380 F	381 F	406* F	410 F	412/ F	414 F
rock type	pillow	pillow	tube gl.	dike	sill gl.	sill
SiO ₂	52.58	52.88	57.91	52.29	57.11	55.04
TiO ₂	0.73	0.69	0.65	0.63	0.46	0.43
Al ₂ O ₃	17.13	16.36	15.59	14.99	15.26	14.30
FeO	9.01	9.10	8.19	8.74	8.19	8.27
MnO	0.16	0.12	0.14	0.13	0.14	0.15
MgO	9.07	9.47	5.78	10.38	6.94	7.53
CaO	7.92	9.16	9.97	11.07	10.88	11.95
Na ₂ O	2.34	1.70	1.62	1.54	0.84	1.83
K ₂ O	0.98	0.43	0.14	0.22	0.19	0.35
P ₂ O ₅	0.08	0.08			0.05	0.02
H ₂ O	3.27	3.12	3.41	6.81	5.76	5.44
CO ₂	0.39	0.18				
Fe ₂ O ₃ /FeO	5.42	3.66				
K	8140	3570	1160	1830	1580	2910
Rb	8	6	3	3	21	8
Sr	98	87	98	82	86	80
Ba	10	10	45	30	43	27
Zr	35+	33+	37	29	24	23
Nb			0.4	0.5	1.2	1.0
Y	21	23	18	17	18	18
Ti	4380	4140	3900	3780	2760	2580
V			277	255	214	201
Cr	177	179	109	173	153	185
Mn	1240	929	1080	1010	1080	1160
Co	30	17				
Ni	48	37				
depth	685	685	790	790	740	735

sample unit	441 F	442 F	443 F	444 F	445 F	446 F
rock type	pillow	pillow	pillow	pillow	pillow	pillow
SiO2	54.70	55.94	54.39	54.56	54.38	53.80
TiO2	0.74	0.83	0.81	0.68	0.57	0.71
Al2O3	15.37	16.41	15.97	15.74	15.07	16.34
FeO	8.07	6.90	7.83	7.65	8.32	5.99
MnO	0.13	0.13	0.15	0.14	0.17	0.16
MgO	5.03	7.64	8.03	8.19	7.97	6.89
CaO	12.91	9.78	10.81	10.91	11.28	13.68
Na2O	2.23	2.20	1.93	1.93	1.92	2.18
K2O	0.75	0.16	0.09	0.12	0.27	0.20
P2O5	0.04	0.01		0.08	0.05	0.05
H2O	3.28	5.19	4.48	5.50	4.34	6.01
CO2						
Fe2O3/FeO						
K	6230	1330	747	996	2240	1660
Rb	18	2	1	2	5	3
Sr	95	102	98	97	90	104
Ba	42	41	36	21	28	37
Zr	35	41	38	37	32	37
Nb	1.2	1.2	0.9	1.6	0.3	0.3
Y	24	22	20	19	23	22
Ti	4440	4980	4860	4080	3420	4260
V	241	317	283	270	230	267
Cr	85	97	109	103	88	112
Mn	1010	1010	1160	1080	1320	1240
Co						
Ni						
depth	745	745	745	745	745	745

sample unit	447 F	448 F	461 F	465 F	468 F	469 F
rock type	pillow	pillow	pillow	large body	large body	sill
SiO2	55.73	53.77	53.24	55.23	54.74	56.15
TiO2	0.71	0.77	0.75	0.67	0.68	0.67
Al2O3	15.02	16.04	16.36	16.66	15.96	15.77
FeO	8.45	8.11	8.17	7.06	8.11	6.94
MnO	0.14	0.13	0.12	0.10	0.11	0.13
MgO	5.51	9.34	9.02	7.68	7.67	8.10
CaO	11.40	10.13	9.76	9.80	10.45	10.10
Na2O	2.17	1.81	2.06	2.58	2.03	1.99
K2O	0.85	0.26	0.49	0.17	0.21	0.13
P2O5	0.05	0.03	0.03	0.04	0.04	0.02
H2O	3.83	6.85	8.10	4.28	4.29	4.63
CO2						
Fe2O3/FeO						
K	7060	2160	4070	1410	1740	1080
Rb	20	3	3	18	3	
Sr	93	94	101	97	92	
Ba	32	39	19	27	40	
Zr	33	36	35	27	36	
Nb	0.6	0.3	1.4	0.3	0.3	
Y	22	22	17	18	18	
Ti	4260	4620	4500	4020	4080	4020
V	233	259	253	243	236	267
Cr	84	106	105	312	101	128
Mn	1080	1010	929	774	852	1010
Co						
Ni						
depth	745	745	745	745	745	690

sample	470	471	473	474	479	483
unit	F	F	F	F	F	F
rock type	sill	sill	sill	sill	large body	dike
SiO2	54.83	55.38	54.58	56.40	55.66	53.04
TiO2	0.62	0.69	0.68	0.65	0.51	0.46
Al2O3	15.91	15.75	15.96	14.87	14.98	15.64
FeO	7.87	7.76	8.46	7.79	7.55	7.51
MnO	0.12	0.12	0.12	0.13	0.11	0.14
MgO	8.41	7.74	7.72	8.38	8.77	9.37
CaO	10.13	10.55	10.34	9.70	10.40	11.91
Na2O	1.94	1.93	1.95	1.96	1.70	1.64
K2O	0.14	0.10	0.14	0.07	0.31	0.27
P2O5	0.03		0.04	0.05	0.02	0.01
H2O	4.97	3.93	4.44	5.44	5.39	4.66
CO2						
Fe2O3/FeO						
K	1160	830	1160	581	2570	2240
Rb	2	1	1	1	2	11
Sr	91	88	88	85	75	72
Ba	27	44	31	30	49	48
Zr	33	33	32	32	21	19
Nb	1.6	0.5	0.9	1.1	0.3	0.3
Y	20	14	18	17	14	17
Ti	3720	4140	4080	3900	3060	2760
V	261	270	254	241	257	202
Cr	112	122	98	110	201	270
Mn	929	929	929	1010	852	1080
Co						
Ni						
depth	690	690	690	690	693	690

sample	484
unit	F
rock type	sill
SiO2	54.39
TiO2	0.60
Al2O3	15.55
FeO	7.98
MnO	0.12
MgO	8.79
CaO	10.38
Na2O	1.97
K2O	0.18
P2O5	0.03
H2O	4.93
CO2	
Fe2O3/FeO	
K	1490
Rb	2
Sr	83
Ba	40
Zr	32
Nb	0.3
Y	23
Ti	3600
V	259
Cr	146
Mn	929
Co	
Ni	
depth	770

sample	171	172	173*	177	180	450
unit	G	G	G	G	G	G
rock type	pillow	pillow	pill.gl.	s.flow	pillow	s.flow
SiO2	52.14	54.35	56.55	58.41	53.87	54.97
TiO2	0.71	0.66	0.63	0.66	0.71	0.68
Al2O3	16.62	15.02	16.20	15.56	16.48	15.12
FeO	8.50	9.11	7.56	7.39	9.26	8.01
MnO	0.13	0.20	0.12	0.09	0.14	0.11
MgO	9.40	9.03	6.09	5.38	7.96	6.26
CaO	10.64	9.98	10.18	9.36	9.24	11.42
Na2O	1.69	1.26	2.45	2.70	2.12	2.45
K2O	0.10	0.33	0.16	0.38	0.18	0.95
P2O5	0.06	0.05	0.05	0.08	0.05	0.04
H2O	2.82	3.98	2.48	1.46	3.70	4.06
CO2	0.35	0.34		0.42	0.14	
Fe2O3/FeO	1.67	0.63		1.91	3.09	
K	830	2740	1330	3150	1490	7890
Rb	6	9		10	6	16
Sr	95	81		100	126	93
Ba	51	35		28	44	31
Zr	35+	31+		38+	41+	40
Nb						2.2
Y	19	20		21	21	25
Ti	4260	3960	3780	3960	4260	4080
V						224
Cr	276	253		177	134	141
Mn	1010	1550	929	697	1080	852
Co	39	40		28	46	
Ni	63	55		55	50	
depth	830	830	830	850	850	845

sample	451	454
unit	G	G
rock type	s.flow	tube
SiO2	57.02	54.62
TiO2	0.65	0.68
Al2O3	14.55	15.56
FeO	7.63	8.10
MnO	0.08	0.13
MgO	6.78	8.30
CaO	10.05	10.58
Na2O	2.35	1.96
K2O	0.83	0.04
P2O5	0.06	0.04
H2O	4.24	4.52
CO2		
Fe2O3/FeO		
K	6890	332
Rb	17	1
Sr	96	97
Ba	28	26
Zr	40	40
Nb	2.0	1.0
Y	26	24
Ti	3900	4080
V	230	245
Cr	160	125
Mn	620	1010
Co		
Ni		
depth	845	855

sample unit	190 H	191 H	192 H	193 H	194 H	362* H
rock type	pillow	pillow	pillow	pillow	pillow	hyalocl.
SiO2	56.78	57.24	60.67	55.65	55.93	57.04
TiO2	0.71	0.65	0.61	0.68	0.67	0.61
Al2O3	16.67	15.52	13.73	15.79	15.59	15.32
FeO	7.30	7.40	8.91	8.07	8.29	7.81
MnO	0.18	0.09	0.20	0.13	0.12	0.18
MgO	7.25	7.27	7.52	7.88	7.74	6.26
CaO	8.00	8.90	5.33	8.61	8.10	10.01
Na2O	2.40	2.75	2.85	2.53	2.86	2.60
K2O	0.66	0.09	0.11	0.58	0.64	0.17
P2O5	0.06	0.07	0.06	0.07	0.06	
H2O	2.47	1.84	2.75	2.72	2.33	5.01
CO2	0.90	0.88	0.28	0.42	1.20	
Fe2O3/FeO	1.78	1.92	4.34	4.03	5.27	
K	5480	747	913	4810	5310	1410
Rb	10	6	8	9	11	
Sr	94	94	88	113	118	
Ba	43	53	22	64	45	
Zr	39+	38+	36+	39+	38+	
Nb						
Y	19	21	19	20	19	
Ti	4260	3900	3660	4080	4020	3660
V						
Cr	211	199	184	171	181	
Mn	1390	697	1550	1010	929	1390
Co	20	35	40	37	35	
Ni	52	59	63	60	59	
depth	900	900	900	925	925	900

sample unit	369* H
rock type	pill.gl.
SiO2	55.87
TiO2	0.88
Al2O3	14.87
FeO	11.51
MnO	0.25
MgO	11.23
CaO	5.23
Na2O	0.29
K2O	0.68
P2O5	
H2O	10.48
CO2	
Fe2O3/FeO	
K	5640
Rb	
Sr	
Ba	
Zr	
Nb	
Y	
Ti	5280
V	
Cr	
Mn	1940
Co	
Ni	
depth	930

sample	200	204	205*	486	487	488
unit	I	I	I	I	I	I
rock type	dike	s.flow	s.flow gl.	dike	s.flow	s.flow
SiO2	51.32	53.66	59.70		55.73	61.11
TiO2	0.50	0.55	1.04		0.72	1.08
Al2O3	16.44	1.29	13.90		16.01	15.07
FeO	8.34	8.09	11.29		8.71	8.66
MnO	0.25	0.15	0.22		0.08	0.22
MgO	9.80	9.08	3.08		5.47	3.16
CaO	11.53	11.26	7.62		8.98	6.54
Na2O	1.69	1.71	2.93		3.08	2.98
K2O	0.08	0.14	0.24		0.72	1.07
P2O5	0.04	0.06			0.08	0.10
H2O	2.49	1.70	7.45		4.71	2.66
CO2	0.21	0.12				
Fe2O3/FeO	3.45	1.43				
K	664	1160	1990		5980	8880
Rb	3	6		2	19	25
Sr	88	87		77	103	89
Ba	49	29				54
Zr	26+	31+		25	52	48
Nb				0.3	0.5	0.7
Y	16	17		12	28	23
Ti	3000	3300	6230		4320	6470
V						460
Cr	457	346				25
Mn	1940	1160	1700		620	1700
Co	43	33				
Ni	81	83				
depth	965	1010	1010	965	945	955

sample	489
unit	I
rock type	dike
SiO2	53.93
TiO2	0.43
Al2O3	14.93
FeO	7.50
MnO	0.14
MgO	10.67
CaO	10.87
Na2O	1.36
K2O	0.12
P2O5	0.04
H2O	6.29
CO2	
Fe2O3/FeO	
K	996
Rb	1
Sr	50
Ba	38
Zr	15
Nb	1.1
Y	17
Ti	2580
V	227
Cr	271
Mn	1080
Co	
Ni	
depth	980

sample	213	214*	221	335*	492	496
unit	J	J	J	J	J	J
rock type	pillow	pill.gl.	tube	s.flow gl.	pillow	dike
SiO ₂	57.44	56.70	52.45	58.28	52.58	
TiO ₂	0.75	0.62	0.70	0.74	0.81	
Al ₂ O ₃	17.80	15.33	17.15	14.56	16.10	
FeO	9.09	8.00	8.22	10.17	11.74	
MnO	0.18	0.11	0.13	0.16	0.21	
MgO	8.42	6.23	8.42	4.43	6.32	
CaO	2.65	10.43	10.82	8.79	9.73	
Na ₂ O	3.32	2.45	1.99	2.63	2.19	
K ₂ O	0.28	0.14	0.05	0.23	0.26	
P ₂ O ₅	0.07		0.07		0.06	
H ₂ O	2.12	4.83	2.36	5.91	5.38	
CO ₂	1.07		0.25			
Fe ₂ O ₃ /FeO	1.05		2.18			
K	2320	1160	415	1910	2160	
Rb	9		4		4	3
Sr	97		101		97	93
Ba	25		64		21	
Zr	41+		39+		41	34
Nb					0.3	1.0
Y	23		20		22	18
Ti	4500	3720	4200	4440	4860	
V					345	
Cr	233		208		25	
Mn	1390	852	1010	1240	1630	
Co	39		37			
Ni	70		66			
depth	1050	1050	1130	1070	940	940

sample unit	235 K	237* K	245 K	246 K	242* K	249* K
rock type	pillow	pill.gl.	s.flow	pillow	pill.gl.	dike
SiO2	66.37	59.87	52.93	64.51	61.63	52.87
TiO2	1.06	1.40	1.42	1.16	1.54	0.50
Al2O3	13.46	14.27	15.74	13.92	13.85	14.02
FeO	8.21	11.32	12.91	8.90	10.75	9.11
MnO	0.19	0.18	0.19	0.16	0.17	0.11
MgO	2.73	2.99	4.82	2.89	2.47	10.62
CaO	4.12	6.50	7.91	5.01	6.73	11.07
Na2O	3.44	3.24	3.18	3.01	2.57	1.53
K2O	0.30	0.23	0.73	0.32	0.30	0.10
P2O5	0.14		0.16	0.12		0.05
H2O	1.77	8.00	1.76	1.68	9.75	2.35
CO2	0.09		0.26	0.28		0.88
Fe2O3/FeO	2.32		1.94	17.15		2.04
K	2490	1910	6060	2660	2490	830
Rb	10		18	11		3
Sr	86		100	120		52
Ba	20		18	31		56
Zr	76+		53+	71+		22+
Nb						
Y	39		39	35		16
Ti	6350	8390	8510	6950	9230	3000
V						
Cr	12		51	18		599
Mn	1470	1390	1470	1240	1320	852
Co						50
Ni	9		18	9		1020
depth	1300	1300	1410	1410	1340	1480

sample unit	336B* K	428 K	429 K	498* K	503 K	516* K
rock type	hyalocl.	dike	dike	hyalocl.	dike	hyalocl.
SiO2	60.43	55.16	53.38	59.74	54.62	64.37
TiO2	1.18	0.51	0.45	1.05	0.62	1.33
Al2O3	14.31	13.36	12.46	14.68	15.65	14.90
FeO	10.27	8.86	9.07	11.41	7.85	10.09
MnO	0.15	0.11	0.13	0.15	0.13	0.16
MgO	3.02	10.39	12.89	3.47	7.91	2.17
CaO	7.34	9.93	9.88	8.36	11.06	6.28
Na2O	3.06	1.54	1.57	0.96	2.05	0.39
K2O	0.24	0.13	0.15	0.18	0.04	0.31
P2O5		0.02	0.02		0.06	
H2O	7.82	6.20	6.62	5.16	5.35	10.52
CO2						
Fe2O3/FeO						
K	1990	1080	1250	1490	332	2570
Rb		1	8		1	
Sr		46	46		92	
Ba		37	40		20	
Zr		20			40	
Nb		1.2			1.2	
Y		14			22	
Ti	7070	3060	2700	6290	3720	7970
V		253	241		222	
Cr		331	612		152	
Mn	1160	852	1010	1160	1010	1240
Co						
Ni						
depth	1300	1400	1400	1480	1300	1490

sample unit	518E* K	518I/ K	521 K	524 K	534/ K
rock type	hyalocl.	dike gl.	dike	pillow	dike gl.
SiO2	63.88	57.48			57.47
TiO2	1.21	0.60			0.63
Al2O3	14.56	15.37			16.54
FeO	10.37	7.89			8.71
MnO	0.15	0.12			0.10
MgO	2.38	6.52			5.03
CaO	6.75	10.17			8.13
Na2O	0.53	1.72			2.69
K2O	0.17	0.12			0.71
P2O5					
H2O	8.25	3.58			1.37
CO2					
Fe2O3/FeO					
K	1410	996			5890
Rb			1	7	
Sr			44	93	
Ba					
Zr			18	73	
Nb			0.3	0.3	
Y			16	35	
Ti	7250	3600			3780
V					
Cr					
Mn	1160	929			774
Co					
Ni					
depth	1510	1510	1520	1520	1400

sample unit	248 L	258/ L	256/ L	262 L	523 L	526 L
rock type	s.flow	dike gl.	dike gl.	pillow	dike	pillow
SiO2	60.68	65.15	64.04	55.08	62.36	
TiO2	1.16	1.08	1.18	1.29	1.33	
Al2O3	14.38	13.87	13.90	15.92	15.00	
FeO	10.43	8.85	9.06	11.26	8.52	
MnO	0.22	0.17	0.18	0.19	0.19	
MgO	5.03	1.74	1.73	6.58	1.83	
CaO	3.52	5.64	5.91	2.78	5.52	
Na2O	3.49	3.24	3.69	2.59	3.92	
K2O	0.98	0.25	0.30	4.20	0.23	
P2O5	0.10			0.11		
H2O	3.16	9.60	6.97	4.96	2.97	
CO2	0.43			0.34		
Fe2O3/FeO	2.53			9.28		
K	8140	2080	2490	34900	1910	
Rb	8			23		1
Sr	66			39		89
Ba	80			66		
Zr	50			54+	83	71
Nb						0.9
Y	30			29	49	35
Ti	6950	6470	7070	7730	7970	
V						
Cr	25			53	20	
Mn	1700	1320	1390	1470	1470	
Co	32			52		
Ni	6			21		
depth	1530	1530	1530	1590	1520	1500

sample unit	527 L	529 L	530 L
rock type	dike	sill	pillow
SiO2	58.45		
TiO2	1.16		
Al2O3	15.09		
FeO	10.95		
MnO	0.13		
MgO	5.19		
CaO	5.67		
Na2O	2.85		
K2O	0.37		
P2O5	0.14		
H2O	5.72		
CO2			
Fe2O3/FeO			
K	3070		
Rb	1	1	9
Sr	73	82	68
Ba			
Zr	50	55	74
Nb	0.3	0.5	1.4
Y	32	32	37
Ti	6950		
V			
Cr	20		
Mn	1010		
Co			
Ni			
depth	1500	1450	1450

Table A.13 Major and trace element compositions of glass separates

sample unit rock type	305 A large body	313 C s.flow	315 C dike	316 C dike	331 G s.flow	336 K hyalocl.
SiO ₂	53.68	58.08	55.84	53.36	56.10	58.69
TiO ₂	0.66	1.25	0.57	0.71	0.65	1.28
Al ₂ O ₃	15.28	13.57	15.10	15.81	14.70	15.02
Fe ₂ O ₃	1.12		0.81	0.68	0.99	2.71
FeO	6.90	12.29	7.31	6.88	6.89	8.26
MnO	0.17	0.21	0.16	0.14	0.14	0.19
MgO	8.36	3.56	6.69	7.84	7.43	3.30
CaO	11.73	7.98	11.24	12.42	10.60	7.63
Na ₂ O	1.90	2.82	2.01	2.05	2.32	2.98
K ₂ O	0.14	0.22	0.23	0.11	0.17	0.28
P ₂ O ₅	0.06		0.03		0.01	0.06
H ₂ O	2.41	6.96	2.98	1.97	2.52	5.37
K	1180	1790	1890	939	1380	2320
Rb	3.13		5.64	2.17	3.67	
Cs	0.124	0.272	0.252			
Sr	69.80	90.00	8710.00	97.50	91.60	
Ba	14.90	26.50	25.50	16.90	21.50	
Hf			0.88	0.95	1.23	
Zr	28	48	27	29	22+	62
Ta			0.098	0.039	0.067	
Nb	0.4	0.8	0.5	0.8	0.3	0.5
Th			0	0	0	
Y	13	28	19	22	14	36
Sc			34.00	34.90	33.90	
Ti	3960	7490	3420	4260	3900	7670
V				215	209	
Cr			67	215	195	
Mn	1320	1630	1240	1080	1080	1470
Co			32	35	34	
Ni			12	56	68	
La	1.14	1.60	1.12	1.41	1.59	2.60
Ce	3.48	5.88	3.01	4.22	4.69	7.94
Nd	3.64	5.96	2.86	4.03	4.47	7.70
Sm	1.47	2.32	1.15	1.52	1.70	2.86
Eu	0.584	0.929	0.462	0.619	0.635	1.100
Gd	2.25	3.70	1.65	2.25	2.43	4.24
Dy	2.95	4.70	2.33	2.76	3.18	5.40
Er	1.93	3.13	1.56	1.85	2.08	3.53
Yb	1.89	3.09	1.57	1.79	2.06	3.49
Lu	0.293	0.476	0.231	0.266	0.312	0.541
depth	130	285	292	275	845	1300

+ recalculated Zr concentrations (see chapter 4)

sample unit rock type	340 A pillow	343 E s.flow	345 E dike	346 E dike	350 F pillow	353 L hyalocl.
SiO2	53.08	50.66	56.01	57.06	54.75	63.95
TiO2	0.67	0.67	0.45	0.73	0.64	1.07
Al2O3	16.13	14.62	14.20	14.50	15.47	13.57
Fe2O3	1.47		0.90	1.89	1.07	1.76
FeO	7.01	7.54	6.99	8.47	7.27	7.19
MnO	0.17	0.25	0.16	0.18	0.15	0.17
MgO	7.62	11.75	7.98	5.10	7.10	1.95
CaO	11.57	13.21	11.24	9.27	11.11	5.78
Na2O	2.14	1.15	1.86	2.53	2.21	3.82
K2O	0.16	0.19	0.20	0.24	0.19	0.58
P2O5	0.02			0.01	0.04	0.12
H2O	3.18	3.29	3.15	3.88	2.40	5.82
K	1290	1550	1660	1980	1550	4850
Rb	3.31	3.64	5.36	5.08	4.06	6.87
Cs	0.150	0.128	0.238			
Sr	79.80	117.00	68.40	95.60	92.50	97.30
Ba	18.00	27.50	22.10	22.40	22.00	38.40
Hf			0.77	1.22	1.13	2.79
Zr	34	40	22	38+	33+	85
Ta			0.071	0.059	0.052	0.100
Nb	0.8	0.7	1.2			1.1
Th			0	0	0	0
Y	17	28	14	23	17	47
Sc			38.30	35.40	36.40	21.60
Ti	4020	4020	2700	4380	3840	6410
V	229		237	281	235	63
Cr	168		264	6	137	3
Mn	1320	1940	1240	1390	1160	1320
Co			34	36	34	14
Ni	37		62	18	30	8
La	1.43	2.16	0.88	1.66	1.60	3.56
Ce	4.24	6.00	2.39	4.92	4.87	10.90
Nd	4.16	5.31	2.43	4.58	4.29	10.40
Sm	1.58	1.93	1.03	1.75	1.62	3.85
Eu	0.623	0.776	0.419	0.683	0.636	1.350
Gd	2.44	2.82	1.63	2.61	2.40	5.55
Dy	3.08	3.47	2.16	3.29	3.04	6.98
Er	1.99	2.60	1.44	2.19	2.00	4.68
Yb	1.94	2.24	1.44	2.15	1.94	4.59
Lu	0.299	0.341	0.217	0.333	0.293	0.689
depth	130	575	550	550	790	1520

sample unit rock type	363 H pillow	368 I hyalocl.	370 I s.flow	371 J pillow	415 F sill	500 L pillow
SiO2	56.29	56.05	59.89	56.34	57.62	60.60
TiO2	0.68	1.00	1.10	0.64	0.80	1.16
Al2O3	15.79	14.99	13.76	14.52	14.80	14.00
Fe2O3		2.34	1.91	1.23	2.18	
FeO	8.00	8.44	9.07	6.57	8.45	11.72
MnO	0.15	0.19	0.18	0.14	0.18	0.18
MgO	7.01	5.48	3.30	7.57	4.43	3.32
CaO	9.39	8.72	7.73	10.54	8.72	7.91
Na2O	2.30	2.55	2.79	2.27	2.51	0.92
K2O	0.21	0.20	0.24	0.17	0.25	
P2O5	0.06	0.04	0.03			
H2O		3.15	3.89	2.22	4.63	5.07
K	1730	1680	1960	1380	2090	
Rb	4.09	4.52	5.20	3.38	5.84	
Cs	0.193				0.250	
Sr	113.00	91.10	80.60	90.90	94.20	
Ba	27.20	28.10	31.40	19.90	22.20	
Hf		1.36	1.65	1.21		
Zr	37	43	48	37	40	43
Ta		0.070	0.058	0.063		
Nb	0.5	0.3	0.9	1.4	1.8	0.7
Th		0	0	0		
Y	20	18	37	22	26	26
Sc		33.40	31.50	33.20		
Ti	4080	6000	6590	3840	4800	6950
V				1		
Cr		9	1	212		
Mn	1160	1470	1390	1080	1390	1390
Co		35	30	32		
Ni		14	8	54		
La	2.16	1.79	2.07	1.58	1.58	1.69
Ce	6.87	5.28	6.14	4.62	5.21	5.19
Nd	6.29	5.21	6.09	4.41	4.94	5.12
Sm	2.37	2.03	2.37	1.67	1.90	2.00
Eu	0.910	0.814	0.893	0.644	0.724	0.784
Gd	3.57	3.07	3.33	2.47	2.84	3.08
Dy	4.48	4.21	4.34	3.14	3.59	4.00
Er	2.94	2.85	2.92	2.07	2.37	2.71
Yb	2.88	2.90	2.84	2.05	2.33	2.72
Lu	0.447	0.389	0.424	0.320	0.365	0.422
depth	925	965	1020	1070	745	1530

sample unit rock type	544 D pillow	KA Kalavassos pillow	LIM Limni pillow
SiO2	51.55	55.01	58.35
TiO2	0.75	0.42	0.29
Al2O3	16.04	15.15	14.37
Fe2O3	1.29	1.47	
FeO	6.69	6.25	7.15
MnO	0.16	0.15	0.11
MgO	8.92	8.43	7.46
CaO	12.34	11.38	10.71
Na2O	2.11	1.61	1.38
K2O	0.10	0.13	0.22
P2O5	0.05	0.12	
H2O	2.22	2.77	3.18
K	836	1040	1840
Rb	1.85	2.90	6.16
Cs	0.058	0.090	0.415
Sr	98.10	83.00	72.20
Ba	14.60	26.10	19.50
Hf			
Zr	37	17	33
Ta			
Nb	0.3	1.2	0.6
Th			
Y	20	8	10
Sc			
Ti	4500	2520	1740
V			
Cr			
Mn	1240	1160	852
Co			
Ni			
La	1.49	1.15	0.69
Ce	4.67	2.79	1.75
Nd	4.67	2.51	1.49
Sm	1.74	0.84	0.63
Eu	0.701	0.351	0.256
Gd	2.55	1.32	1.01
Dy	3.25	1.78	1.56
Er	2.06	1.24	1.12
Yb	1.97	1.28	1.19
Lu	0.309	0.200	0.191
depth	385		

Table A.14 Isotopic compositions of glass separates

sample	$^{87}\text{Sr}/^{86}\text{Sr}$ unleached	$^{87}\text{Sr}/^{86}\text{Sr}$ leached	$^{87}\text{Sr}/^{86}\text{Sr}$ T=80	$^{87}\text{Rb}/^{86}\text{Sr}$
305	0.703906±47		0.703758	0.1300
313	0.704033±22			
315	0.704324±21		0.703711	0.1873
316	0.703327±22	0.703334±28	0.703253	0.0644
331	0.703851±28		0.703710	0.1159
336				
340	0.703927±21		0.703792	0.1184
343	0.703552±15		0.703250	0.0900
345	0.704262±30		0.704004	0.2265
346	0.703781±30	0.703803±14	0.703606	0.1536
350	0.704005±22	0.704004±20	0.703861	0.1269
353	0.703910±30	0.703931±20	0.703678	0.2043
363	0.704108±15		0.703988	0.1051
368	0.703659±20		0.703496	0.1434
370	0.704010±30		0.703682	0.1866
371	0.703480±30		0.703741	0.1076
415	0.703919±11		0.703715	0.1792
500				
544	0.703194±22	0.703194±22	0.703132	0.0545
KA	0.703553±18	0.703553±18	0.703414	0.1010
LIM	0.704637±13	0.704637±12	0.704357	0.2457

sample	$^{143}\text{Nd}/^{144}\text{Nd}$ measured	$^{143}\text{Nd}/^{144}\text{Nd}$ T=80	$^{147}\text{Sm}/^{144}\text{Nd}$	$\epsilon\text{Nd}(80)$
305	0.513052±18	0.512924	0.2438	7.59
313	0.513033±17	0.512910	0.2355	7.31
315	0.513007±24	0.512882	0.2391	6.77
316	0.513032±20	0.512913	0.2276	7.37
331	0.513041±31	0.512921	0.2303	7.52
336	0.513017±10	0.512899	0.2248	7.11
340	0.513048±19	0.512928	0.2301	7.67
343	0.512987±16	0.512872	0.2201	6.58
345	0.513000±12	0.512867	0.2545	6.48
346	0.513011±17	0.512891	0.2302	6.94
350	0.513021±22	0.512902	0.2283	7.15
353	0.513035±19	0.512918	0.2231	7.48
363	0.513020±13	0.512901	0.2274	7.14
368	0.513045±21	0.512922	0.2348	7.56
370	0.513011±23	0.512888	0.2353	6.89
371	0.513017±32	0.512897	0.2290	7.07
415	0.513002±17	0.512880	0.2329	6.73
500	0.513035±20	0.512912	0.2355	7.35
544	0.513032±14	0.512915	0.2233	7.56
KA	0.513035±27	0.512917	0.2255	7.45
LIM	0.512952±20	0.512818	0.2568	5.52

sample	208Pb/204Pb	207Pb/204Pb	206Pb/204Pb	8180
305	38.527	15.580	18.628	
313	38.658	15.594	18.726	
315				5.76
316	38.438	15.566	18.597	5.66
331				5.41
336				
340	38.554	15.576	18.656	6.10
343				
345	38.505	15.590	18.704	5.90
346	38.084	15.564	18.603	5.61
350	38.425	15.560	18.649	5.35
353	38.473	15.553	18.617	13.80
363				
368				6.49
370				6.48
371	38.548	15.572	18.710	5.22
415	38.526	15.588	18.646	
500	38.653	15.599	18.702	
544	38.400	15.543	18.488	
KA	38.534	15.549	18.792	
LIM	38.463	15.594	18.577	

Table A.15 Major and trace element compositions of selected whole rocks

sample unit rock type	31 A pillow	111 D pillow	233 K pillow	259 L pillow	504 K sill	506 L dike
SiO ₂	53.86	52.11	53.96	57.73	56.63	53.28
TiO ₂	0.62	0.72	1.42	1.26	0.59	0.61
Al ₂ O ₃	17.11	17.26	15.42	15.38	13.74	14.28
Fe ₂ O ₃						
FeO	9.73	9.56	11.96	10.17	8.23	9.70
MnO	0.07	0.12	0.16	0.08	0.16	0.19
MgO	8.37	11.31	4.89	5.69	9.22	11.13
CaO	2.24	6.11	7.83	5.37	8.63	7.92
Na ₂ O	0.25	1.55	3.52	2.72	2.39	2.07
K ₂ O	7.83	1.22	0.77	1.45	0.37	0.69
P ₂ O ₅	0.08	0.03	0.08	0.15	0.05	0.05
H ₂ O	8.53	5.43	2.61	5.36	3.05	6.17
K	65000	10100	6390	12000	3070	5740
Rb		9.00	13.00	10.00	3.00	3.54
Cs						0.031
Sr		78.00	93.00	89.00	62.00	68.00
Ba			11.00	52.00	31.00	22.80
Hf						
Zr	32	35	60	59	23	26
Ta						
Nb		2.2	0.3	1.2	0.8	1.5
Th						
Y	21	22	32	32	16	18
Sc						
Ti	3720	4320	8510	7550	3540	3660
V					252	
Cr	200	143	55	44	321	
Mn	542	929	1240	620	1240	1470
Co	36	35		36		
Ni	87	36	17	17		
La	1.95	1.83	2.27	2.22	1.11	1.00
Ce	6.25	5.81	7.23	6.94	3.05	3.08
Nd	6.15	5.45	7.17	7.13	2.88	3.04
Sm	2.37	2.13	2.71	2.71	1.16	1.22
Eu	0.964	0.828	1.100	1.060	0.457	0.495
Gd	3.47	3.00	3.95	4.12	1.82	1.93
Dy	4.49	3.72	4.84	4.89	2.33	2.48
Er	2.90	2.27	3.13	3.03	1.56	1.65
Yb	2.77	1.97	3.04	2.69	1.54	1.62
Lu	0.417	0.303	0.466	0.500	0.244	0.250
depth	15	365	1300	1550	1450	1950

sample unit rock type	507 L pillow	509 L pillow
SiO2	59.67	53.55
TiO2	0.96	0.77
Al2O3	14.43	15.76
Fe2O3		
FeO	9.58	10.13
MnO	0.27	0.26
MgO	6.46	8.84
CaO	4.31	5.35
Na2O	4.23	5.12
K2O	0.02	0.15
P2O5	0.06	0.06
H2O	5.67	6.28
K	166	1250
Rb	0.40	2.00
Cs		
Sr	21.00	30.00
Ba	49.00	24.00
Hf		
Zr	35	29
Ta		
Nb	1.1	0.3
Th		
Y	22	19
Sc		
Ti	5760	4620
V		
Cr	259	57
Mn	2090	2010
Co		
Ni		
La	1.81	1.22
Ce	4.85	3.79
Nd	4.20	3.70
Sm	1.56	1.42
Eu	0.570	0.563
Gd	2.41	2.17
Dy	3.08	2.77
Er	1.97	1.83
Yb	1.89	1.78
Lu	0.267	0.263
depth	1990	1990

Table A.16 Isotopic compositions of selected whole rocks

sample	$^{143}\text{Nd}/^{144}\text{Nd}$ measured	$^{143}\text{Nd}/^{144}\text{Nd}$ T=80	$^{147}\text{Sm}/^{144}\text{Nd}$	$\epsilon\text{Nd}(80)$
31	0.512973 $\pm$ 13	0.512851	0.2331	6.17
111	0.512989 $\pm$ 15	0.512866	0.2347	6.46
233	0.513047 $\pm$ 14	0.512928	0.2282	7.66
159	0.513022 $\pm$ 13	0.512902	0.2296	7.16
504	0.512992 $\pm$ 14	0.512865	0.2435	6.43
506	0.513001 $\pm$ 14	0.512874	0.2429	6.60
507	0.513035 $\pm$ 19	0.512917	0.2249	7.50
509	0.513021 $\pm$ 21	0.512900	0.2314	7.10

Table A.17 Compositions of whole rocks (WR) and altered glasses (AG)

sample	305WR	313WR	315WR	316WR	316AG	331WR
SiO ₂	56.50	54.79	54.65	53.50		51.88
TiO ₂	0.63	1.26	0.59	0.62		0.46
Al ₂ O ₃	15.20	14.45	16.22	15.95		17.08
Fe ₂ O ₃		8.38		1.66		6.38
FeO	7.52	5.53	9.06	5.96		3.26
MnO	0.11	0.16	0.15	0.13		0.16
MgO	7.99	5.89	7.43	8.42		7.06
CaO	9.50	6.46	9.27	11.60		11.21
Na ₂ O	2.01	2.42	1.98	1.97		2.06
K ₂ O	0.48	0.54	0.56	0.23	0.62	0.34
P ₂ O ₅	0.06	0.12	0.09	0.03		0.11
H ₂ O	4.85	8.12	4.74	3.44		3.41
K	3980	4480	4650	1920	5140	2820
Rb	1.00	8.00	4.00	3.36	11.70	10.00
Cs						
Sr	89.00	113.00	82.00	101.00	68.00	70.00
Ba				18.70	7.93	

sample	336WR	336AG	340WR	345WR	345AG	346WR
SiO ₂	58.03		53.09	56.32		57.01
TiO ₂	1.23		0.73	0.46		0.75
Al ₂ O ₃	14.77		16.52	15.34		14.78
Fe ₂ O ₃	4.00		6.20	5.39		
FeO	7.13		2.63	2.63		10.26
MnO	0.21		0.08	0.08		0.19
MgO	3.59		8.99	8.27		6.12
CaO	7.10		9.42	9.43		7.92
Na ₂ O	3.38		1.94	1.86		2.47
K ₂ O	0.42	0.27	0.30	0.17	0.29	0.41
P ₂ O ₅	0.14		0.10	0.06		0.09
H ₂ O	5.96		6.35	5.21		3.18
K	3490	2280	2460	1420	2380	3400.00
Rb	3.00	4.91	4.47	3.00	3.70	
Cs		0.320	0.052	0.086	0.112	
Sr	98.00	11.00	102.00	66.80	55.40	
Ba		33.80	7.39	14.00	16.00	

sample	350WR	353WR	368WR	370WR	371WR	371AG
SiO ₂	53.36	62.29	53.97	59.51	55.38	
TiO ₂	0.81	1.12	0.96	1.08	0.63	
Al ₂ O ₃	16.24	14.44	16.14	14.62	15.16	
Fe ₂ O ₃	6.19	2.84			2.47	
FeO	2.35	6.64	11.09	11.06	5.64	
MnO	0.10	0.17	0.11	0.17	0.15	
MgO	9.21	2.38	7.44	4.45	8.09	
CaO	9.02	5.58	6.32	6.34	10.02	
Na ₂ O	2.31	3.50	3.22	2.29	2.12	
K ₂ O	0.27	0.74	0.65	0.37	0.29	0.74
P ₂ O ₅	0.11	0.20	0.11	0.11	0.05	
H ₂ O	5.99	6.87	6.88	8.34	5.28	
K	2270	6140	5400	3070	2410	6140
Rb	4.33	6.00	9.00	6.00	4.00	16.00
Cs	0.046					
Sr	96.80	104.00	69.00	101.00	95.00	162.00
Ba						36.30

sample	406WR	412WR	415WR	500WR	500AG	544WR
SiO2	55.39	54.73	54.34	58.38		50.99
TiO2	0.74	0.42	0.73	1.04		0.85
Al2O3	15.81	14.76	15.08	14.09		16.74
Fe2O3						7.75
FeO	7.78	7.99	10.61	11.04		
MnO	0.13	0.14	0.20	0.18		0.14
MgO	8.52	8.18	7.07	4.47		10.24
CaO	9.44	11.24	9.16	8.05		10.00
Na2O	1.97	2.13	1.97	2.27		2.62
K2O	0.17	0.35	0.72	0.45	0.37	0.58
P2O5	0.04	0.05	0.12	0.03		0.09
H2O	5.68	5.00	5.77	3.88		5.96
K	1410	2910	5980	3740	3080	4810
Rb			14.00	8.00	4.80	5.00
Cs					1.070	
Sr			92.00	78.00	217.00	92.00
Ba					83.80	

sample	KAWR	LIMWR
SiO2	55.92	54.86
TiO2	0.36	0.47
Al2O3	14.90	13.93
Fe2O3	4.38	2.82
FeO	4.30	5.40
MnO	0.13	0.18
MgO	10.17	11.43
CaO	8.36	9.15
Na2O	1.07	1.40
K2O	0.41	0.34
P2O5		
H2O	10.55	7.29
K	3400	2820
Rb	9.00	8.00
Cs		
Sr	91.00	73.00
Ba		

sample	340WR
La	1.52
Ce	4.38
Nd	4.20
Sm	1.57
Eu	0.635
Gd	2.39
Dy	3.00
Er	1.97
Yb	1.94

Table A.18 Isotopic compositions of altered glasses and whole rock corresponding to glass separates

sample	$^{87}\text{Sr}/^{86}\text{Sr}(\text{m})$	$^{143}\text{Nd}/^{144}\text{Nd}(\text{m})$	$\delta^{18}\text{O}$
313AG	0.704850 ± 28		
316AG	0.704735 ± 12		19.44
316WR	0.704516 ± 25		9.33
340AG			6.73
340WR	0.704304 ± 20	0.513042 ± 44	10.87
345AG	0.704765 ± 10		15.30
345WR	0.704538 ± 13		10.71
371AG	0.704502 ± 21		12.51
371WR			7.52
500AG	0.706031 ± 46		

Table A.19 CIPW normative compositions of glass separates

sample unit	305 A	313 C	315 C	316 C	331 G	336 K
rock type	large body	s.flow	dike	dike	s.flow	hyalocl.
SiO ₂	53.68	58.08	55.84	53.36	56.10	58.69
TiO ₂	0.66	1.25	0.57	0.71	0.65	1.28
Al ₂ O ₃	15.28	13.57	15.10	15.81	14.70	15.02
Fe ₂ O ₃	1.12		0.81	0.68	0.99	2.71
FeO	6.90	12.29	7.31	6.88	6.89	8.26
MnO	0.17	0.21	0.16	0.14	0.14	0.19
MgO	8.36	3.56	6.69	7.84	7.43	3.30
CaO	11.73	7.98	11.24	12.42	10.60	7.63
Na ₂ O	1.90	2.82	2.01	2.05	2.32	2.98
K ₂ O	0.14	0.22	0.23	0.11	0.17	0.28
P ₂ O ₅	0.06		0.03		0.01	0.06
H ₂ O	2.41	6.96	2.98	1.97	2.52	5.37
Qtz	5.08	12.36	8.99	3.66	8.22	16.37
Or	0.84	1.27	1.34	0.67	0.98	1.65
Ab	16.07	23.86	17.01	17.34	19.63	25.11
An	32.73	23.73	31.50	33.59	29.19	26.66
Cpx	20.28	13.54	19.71	22.83	19.01	8.83
Opx	21.97	22.88	19.14	19.61	20.29	14.90
Mgn	1.62		1.17	0.99	1.44	3.91
Ilm	1.26	2.38	1.08	1.35	1.24	2.43
Ap	0.14		0.07		0.02	0.14

sample unit	340 A	343 E	345 E	346 E	350 F	353 L
rock type	pillow	s.flow	dike	dike	pillow	hyalocl.
SiO ₂	53.08	50.66	56.01	57.06	54.75	63.95
TiO ₂	0.67	0.67	0.45	0.73	0.64	1.07
Al ₂ O ₃	16.13	14.62	14.20	14.50	15.47	13.57
Fe ₂ O ₃	1.47		0.90	1.89	1.07	1.76
FeO	7.01	7.54	6.99	8.47	7.27	7.19
MnO	0.17	0.25	0.16	0.18	0.15	0.17
MgO	7.62	11.75	7.98	5.10	7.10	1.95
CaO	11.57	13.21	11.24	9.27	11.11	5.78
Na ₂ O	2.14	1.15	1.86	2.53	2.21	3.82
K ₂ O	0.16	0.19	0.20	0.24	0.19	0.58
P ₂ O ₅	0.02			0.01	0.04	0.12
H ₂ O	3.18	3.29	3.15	3.88	2.40	5.82
Qtz	4.03		8.74	12.00	6.58	22.02
Or	0.92	1.10	1.18	1.41	1.10	3.45
Ab	18.10	9.73	15.74	21.41	18.70	32.33
An	33.92	34.15	29.80	27.50	31.73	18.15
Cpx	18.97	25.38	21.17	15.29	18.86	8.09
Opx	20.63	23.73	21.24	18.26	20.18	11.06
Mgn	2.13		1.31	2.74	1.55	2.55
Ilm	1.27	1.27	0.86	1.39	1.22	2.04
Ap	0.05			0.02	0.10	0.29

sample unit	363 H	368 I	370 I	371 J	415 F	500 L
rock type	pillow	hyalocl.	s.flow	pillow	sill	pillow
SiO2	56.29	56.05	59.89	56.34	57.62	60.60
TiO2	0.68	1.00	1.10	0.64	0.80	1.16
Al2O3	15.79	14.99	13.76	14.52	14.80	14.00
Fe2O3		2.34	1.91	1.23	2.18	
FeO	8.00	8.44	9.07	6.57	8.45	11.72
MnO	0.15	0.19	0.18	0.14	0.18	0.18
MgO	7.01	5.48	3.30	7.57	4.43	3.32
CaO	9.39	8.72	7.73	10.54	8.72	7.91
Na2O	2.30	2.55	2.79	2.27	2.51	0.92
K2O	0.21	0.20	0.24	0.17	0.25	
P2O5	0.06	0.04	0.03			
H2O		3.15	3.89	2.22	4.63	5.07
Qtz	8.47	11.18	18.17	9.00	14.19	25.44
Or	1.23	1.20	1.40	0.98	1.49	
Ab	19.48	21.57	23.60	19.21	21.25	7.80
An	32.17	28.84	24.31	28.93	28.38	34.12
Cpx	11.49	11.63	11.62	19.01	12.42	4.43
Opx	25.71	20.19	15.97	19.90	17.60	26.01
Mgn		3.39	2.77	1.78	3.16	
Ilm	1.30	1.90	2.09	1.22	1.52	2.21
Ap	0.14	0.10	0.07			

sample unit	544 D	KA Kalavasos	LIM Limni
rock type	pillow	pillow	pillow
SiO2	51.55	55.01	58.55
TiO2	0.75	0.42	0.29
Al2O3	16.04	15.15	14.37
Fe2O3	1.29	1.47	
FeO	6.69	6.25	7.15
MnO	0.16	0.15	0.11
MgO	8.92	8.43	7.46
CaO	12.34	11.38	10.71
Na2O	2.11	1.61	1.38
K2O	0.10	0.13	0.22
P2O5	0.05	0.12	
H2O	2.22	2.77	3.18
Qtz	0.43	8.83	14.02
Or	0.60	0.74	1.31
Ab	17.85	13.60	11.67
An	33.98	33.69	32.33
Cpx	21.71	17.57	17.03
Opx	22.02	22.33	23.11
Mgn	1.87	2.13	
Ilm	1.43	0.80	1.22
Ap	0.12	0.29	

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Hiermit erkläre ich, daß ich die Arbeit selbständig und ohne unerlaubte Hilfe ausgeführt und verfaßt habe und daß die Arbeit in dieser oder ähnlicher Form noch bei keiner Fakultät oder anderen Hochschule eingereicht wurde.

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